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# IMPROVED SOLAR STILL PROCESS FOR DESALTING SEA AND BRACKISH WATER

A THESIS

Presented to

the Faculty of the Graduate Division

by

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GLOSSARY

| | | |
|---|---|---|
| $\theta$ | = | angle of sun's rays with horizontal surface, degree |
| U | = | work, cal |
| R | = | gas constant, 1.987 cal/degree/mole |
| T | = | absolute temperature |
| P | = | partial vapor pressure of water above brine at T, atmosphere |
| $P_o$ | = | vapor pressure of pure water at T, atmosphere |
| $i_o$ | = | angle of incidence of direct radiation with a single sheet of glass |
| $I_o$ | = | intensity of radiation incident on a sheet of glass |
| $L_1$ | = | fraction of direct solar energy transmitted through a single sheet of glass |
| $A_1$ | = | fraction of direct solar energy absorbed in a single sheet of glass |
| $R_1$ | = | fraction of direct solar energy available after passage through a single sheet of glass |
| r | = | fraction of direct solar energy reflected from a single sheet of glass |
| g | = | fraction of direct solar energy available after one passage through glass |
| $H_o$ | = | absorbed energy by an absorbent surface in BTU/hr |
| $\epsilon_w$ | = | the spectral absorptivity (measured by experiment) |
| $G_w$ | = | the spectral irradiation from a source (at surface) such as sun, in BTU/hr/sq ft |
| w | = | wavelength of radiation |
| dw | = | differential of wavelength of radiation |
| $\epsilon$ | = | total absorptivity |
| G | = | total irradiation |

$H_{r,i}$ = radiation heat transfer coefficient from basin to cover inside still, BTU/hr/sq ft/°F (conventional design)

$t_g$ = temperature of cover glass, assumed equal to distillate temperature, °F (conventional design)

$t_b$ = temperature of sea water in basin, °F (conventional design)

$W_{da}/W_{H_2O}$ = pounds of dry air circulated in still per pound of water evaporated and condensed (conventional design)

$H_{a_b}$ = enthalpy of dry air at basin temperature, BTU/lb (conventional design)

$H_{a_g}$ = enthalpy of dry air at cover temperature, BTU/lb (conventional design)

$\lambda'$ = heat of vaporization of water at basin temperature, BTU/lb (conventional design)

$H_{sh}$ = adjusted daily solar input BTU/day (conventional design)

$Q_g$ = heat transfer rate from cover to air, BTU/hr (conventional design)

$Q_{bx}$ = heat removed in effluent brine, BTU/day (conventional design)

$Q_{b-a}$ = heat transfer rate from basin to cover (conventional design)

S = sea water charged to still, lbs/day (conventional design)

$E_v$ = water evaporation rate, lbs/hr/sq ft (conventional design)

$h_{1c}$ = convection heat transfer coefficient from cover to atmosphere BTU/hr/sq ft/°F (conventional design)

$h_{1r}$ = radiation heat transfer coefficient from cover to atmosphere BTU/hr/sq ft/°F (conventional design)

$h_{1co}$ = convection heat transfer coefficient from basin to cover inside still, BTU/hr/sq ft/°F (conventional design)

$t_m$ = mean temperature difference between air and droplet surface

$\frac{dw}{dt}$ = evaporation rate, mass per unit time

$h_c$ = heat transfer coefficient for convection and conduction through the film drop

$A_h$ = surface area of drop receiving heat

$\lambda_s$ = latent heat of evaporation corresponding to $t_s$

$(\Delta P)_m$ = mean vapor-pressure corresponding to $t_s$

$P_a$ = the partial pressure of the vapor in the air

$K_g$ = coefficient of mass-transfer

$A_m$ = area of drop from which mass is transferred

$d$ = drop diameter

$K_f$ = thermal conductivity of gas film around drop

$D_v$ = diffusion coefficient of vapor

$P_f$ = mean partial pressure of nondiffusing gas in gas film

$V_a$ = relative velocity between drop and its surroundings

$\rho_a$ = gas film density

$\pi$ = gas film viscosity

$C_p$ = gas film specific heat

$H$ = total solar energy gram-cal/cm$^2$/day

$H_s$ = sky radiation, gram-cal/cm$^2$/day

$H_d$ = direct radiation, gram-cal/cm$^2$/day

$H_a$ = available energy (to run the system) BTU/sq ft

$H_l$ = total heat loss from collector-evaporator unit, BTU/day

$H'_l$ = total heat loss from condenser, BTU/day

$H''_l$ = total heat loss from piping system, BTU/day

$H_{l,c}$ = heat loss by convection from exposed surface of collector, BTU/day

$H_{l,r}$ = radiation loss from collector, BTU/day

$H_{l,co}$ = heat loss by conductance from bottom of collector, BTU/day

$\lambda$ = latent heat of vaporization, BTU/lb at $t''_a$

$E$ = efficiency of the system to collect solar energy

$\beta$ = the ratio of exposed surface of collector to horizontal area

$\beta_1$ = the ratio of unexposed surface of collector to horizontal area

A = surface area of collector, sq ft

D = approximate diameter of top of the collector, ft

$W_a$ = water content of atmosphere, lb/lb of dry air

$W'_a$ = water content of air leaving system, lb/lb of dry air

$W''_a$ = water content of air in collector, lb/lb of dry air

$q_a$ = amount of dry air flowing through, lb/day

$q_s$ = sea water input, lb/day

$q_f$ = fresh water production in day, lb/day

$q'_f$ = fresh water production in night, lb/day

q = $q_f + q'_f$, total of fresh water produced, lb/day

Q' = brine water to waste at beginning of day, lb/day

$\alpha$ = $\frac{q'_f}{q_f}$

$t_a$ = ambient temperature, °F

$t_s$ = incoming sea water, °F

$t'_s$ = temperature of brine leaving condenser, °F

$t_f$ = temperature of fresh water produced during the day, °F

$t'_f$ = temperature of fresh water produced during the night, °F

$t_i$ = temperature within still (average 8 hours daylight), °F

$t_p$ = plastic temperature, °F

$t''_w$ = temperature of air leaving system, °F

$t'_w$ = temperature of water within basin

$t_w$ = temperature of brine in collector, °F

$t'_s$ = temperature of brine leaving condenser, °F

C = heat capacity of air, BTU/lb/°F

$d'$ = insulation thickness, inches

K = mean conductance of insulation under collector, BTU/day/°F/sq ft/in

V = mass velocity of the ambient air lb/day $ft^2$

$\sigma$ = Stefen-Boltman Constant, $.173 \times 10^{-8}$

e = emissivity of plastic sheet

$\omega$ = gas film viscosity

## ABBREVIATIONS

| | | |
|---|---|---|
| bgpd | = | billion gallons (U. S.) per day |
| mg | = | million gallons (U. S.) |
| mgpd | = | million gallons (U. S.) per day |
| hp | = | horse power |
| mil | = | thousandth of an inch |
| I. D. | = | inside diameter |
| gpm | = | gallons per minute |
| cc | = | cubic centimeter |
| emf | = | electro motive force |
| ppm | = | part per million |
| lb | = | pound |
| sq ft | = | square feet |
| BTU | = | British thermal unit |
| cal | = | calorie |
| $cm^2$ | = | square centimeter |
| cfs | = | cubic feet per second |
| ft-sec | = | feet per second |

# CHAPTER I

## INTRODUCTION

Man's quest for fresh water started with creation. Down through the ages mankind has used imagination and many skills to locate and conserve fresh water. People in ancient countries from Babylonia to the Roman Empire dug wells, used extinct volcanic craters as reservoirs, constructed aqueducts, canals, tunnels, and irrigation systems. The growth of cities, the location of new factories, the welfare of households, the raising of livestock, and the cultivation of crops are typical examples of how ultimately all life depends upon the supply of fresh water. Because of growing population and expanding industries, each year the margin is becoming smaller and smaller between fresh water supply and demand.

To illustrate man's quest for water and the futility of over 30 centuries of hydraulic and water works development, the figures* below show the present status of man's ability to intercept water from nature, to harness it and to supply various needs:

| | |
|---|---|
| Moisture in clouds passing over the state of Illinois | 2000 bgd |
| Transpiration | 43 bgd |
| Evaporation | 99 bgd |
| Stream Flow | 23 bgd |
| Industrial Use | 8 bgd |
| Agriculture Use | 7 bgd |
| Domestic Use | 1 bgd |

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*From a paper presented by A. M. Buswell at Georgia Institute of Technology, Atlanta, Georgia, in November 1952.

This shows that in one of the most highly developed states only 0.8 per cent of water has been successfully intercepted and even with cloud seeding there exists a real need for a "break through" of additional sources of potential water supplies.

New sources of fresh water are desperately needed and experimentation to find an economical method of demineralizing brackish and sea water into fresh water is the subject of this dissertation.

Conversion of salt water into fresh has been a dream since ancient times. The recent intensification of interest in this problem can best be appreciated within the context of global water supply and requirements. While the earth is richly endowed with water supplies, most of which are continually recharged, there are some areas of acute water shortage.

Approximately seven-tenths of the earth's surface is covered with water and three-tenths by land. Although the major percentage of this water is too salty for human consumption or agricultural use, there is an abundance of fresh water on the earth. The earth and its atmospheric system act as a gigantic distillation apparatus which continually extracts fresh water from the oceans and deposits rain upon the land, providing water for human use before it flows through rivers back to the sea. It is paradoxical that in spite of abundant supplies of ever-renewed fresh water there are growing water shortages in many areas.

In most regions of the world where the need for fresh water is critical, the greatest intensities of solar radiation are experienced. Solar radiation provides an unlimited and free source of energy which may be successfully harnessed to furnish fresh water from the sea or from brackish waters at an economical cost. Basic characteristics, or properties, of solar energy include its (a) enormous quantity, (b) low concentration at the earth's surface, and (c) variability at a given location.

A conventional solar distiller, although simple in design, equipment and operation, produces only a small amount of water per unit of area. The low efficiency is due to the dispersed form of energy of the sun and also the inherent property of the design. A conventional solar still combines the three processes of collection of solar energy, evaporation, and condensation in the one unit. It relies on natural convection within the still and the cooling effect of ambient air. Large areas of solar stills involving equipment and glass, are required for utilization of solar energy, and therefore costs are high.

Several design features are investigated to improve the yield of presently existing solar stills. One of the improvements is the mechanical separation of the collector-evaporator unit from the condenser. A further improvement is the use of air as an intermediate substance which substitutes forced convection for natural convection. In addition, this design utilizes droplet evaporation in lieu of flat sheet evaporation to increase the interfacial area between carrier and water droplet. These improvements simultaneously increase both the efficiency of collection of solar energy and increase the rate of evaporation. Another important feature of the new design is the re-use of the energy by preheating the incoming sea water in an external heat exchanger.

The new design improves the economy of the system by reducing the area required to produce fresh water. Further economy is realized by substitution of type W, Mylar plastic as transparent material for glass.

# CHAPTER II

## CRITICAL REVIEW OF THE LITERATURE

The quest for water.--Water is essential for human existence; in fact sixty per cent of the human body is composed of water. From times immemorial water supply has played a very important part in man's history. It has influenced the planning of towns and villages, and many projects became impossible for want of water.

"After the passion of love, water rights have caused more trouble than anything else to the human species" (1). Wars were declared for claiming a source of water supply, and lost for inability to obtain it. According to an Arab proverb, there are three things which relieve the heart from sorrow: green grass, beauty of woman, and water. An Indian village song describes the Earth as Mother, the Sky as Father, the Wind as Brother, and the Water as Sweetheart. This Sweetheart is becoming more and more important in the life of Americans as well.

Until recent years, water has not been considered a subject of major importance to the American nation as a whole. To the contrary, it has been widely accepted in much the same way as air and sunshine, a continuing heritage that fulfills its role in life without reference to a beginning or ending, and as a result it is commonly conceived of as inalienable, free, and everlasting. With consternation it is now being discovered that water, air, and light are not alike in abundance; and water, in the sense that in many places it must undergo expensive handling and treatment before use, is far from free for the individual.

Now as always, water is a gift of the skies and the earth, as manifested in a dynamic circuit of moisture with the sun as the source of energy. It is used as needed in that part of its journey that is within reach, and after its temporary service it continues its natural course in unending transport.

Mr. Fred A. Seaton, Secretary of the Interior, recently stated: "We know that the availability of water--just plain, ordinary water--is rapidly becoming a major concern to America and the world. In fact, as early as 1975-80, it may be our number one domestic problem." (2)

The nation is becoming increasingly water conscious, largely because of water problems that have developed in many communities during recent years. In many areas of the United States, Americans are for the first time experiencing water shortages. It is becoming apparent that in many places underground water is exhaustible and that the industrial demand for water is almost beyond comprehension. Americans are finding that adequate water supplies in many cases contribute more to the location of new industry than electric rates, freight rates, or even raw materials (3).

Those who live in well-watered regions of the United States often have little conception of the battle for water in the arid regions of the Southwest. The only way crops can be raised is by the most careful conservation and use of all the water which falls as well as the addition to it of some obtained from other regions. Water in these regions means life or death, and tragedy stalks close behind a failure of supply.

Most people have heard or read of the probable oil shortage, but the idea that there could be a serious water shortage may come to some as a shock. The problem is one of distribution in time and space in order that the needed water may be at the right place at the right time.

Just as some parts of the United States suffer at times from too much water, others are struggling with perennial shortages which are limiting the expansion of agriculture and industry and the growth of many communities, in both East and West (4). The humid eastern states, which have long enjoyed an abundance of water, are becoming uncomfortably aware of the need for conserving this important natural resource (5).

The average rainfall in the United States is about 30 inches, providing 28,000 gallons for each person each day. This would seem to be much more than enough, but 70 per cent of this evaporates and one third of the remainder disappears underground and cannot easily be caught. This leaves 5,600 gallons a day per person which he can have if he can catch it. The total water used averages a little more than 1,100 gallons per day for each person, and therefore efficiency in collecting and using the water provided by rainfall is nearly 20 per cent (6). This figure seems surprisingly high when it is remembered that the rainfall varies so widely over the country and through the four seasons of the year.

Each year the margin is becoming thinner and thinner between fresh water supply and demand because of growing population with higher standard of living and industries.

Few communities of any size can depend any longer upon local, natural streamflow for their normal water supplies. Municipalities need to go farther and farther for their water and incur larger outlays for storage reservoirs, aqueducts, and treatment plants. Such problems are faced, sometimes acutely, by New York, Philadelphia, Baltimore, Louisville, Los Angeles, Tucson, San Francisco, San Diego, Santa Barbara, and a score of other cities. Many a city that only a few short years ago had plenty of water is now running short.

Tucson, Arizona, located in the semi-arid Southwest, illustrates the plight of many Western municipalities. Here rainfall averages only 11.5 inches a year, about a fourth of what Washington, D. C., obtains. Tucson, in fact, can exist only by virtue of underground water supplies derived originally from snow and rain in the mountains south of the city. This water is very hard and alkaline, and must be ammoniated and disinfected to meet Public Health standards.

Some of Tucson's water problems are due to the competition for the same "water holes" by urban residents and farmers. The underground sources that supply the city also furnish water to irrigate 115,000 acres in the Santa Cruz Valley which produce long-staple cotton, livestock feed, dairy products, poultry, and other products. Because there are no state or local restrictions on well-drilling or pumping of underground water, except in highly critical situations, anarchy in pumping operations prevails.

The present crisis is due largely to the phenomenal expansion of Tucson in the last decade. The area was an important war center, supporting extensive Air Force installations and a large airplane assembly plant. Many soldiers who were stationed there decided to go back and make their homes in the sunny city with its salubrious climate. In addition, Tucson has been widely advertised, particularly by the airlines, as a winter resort and health center. The permanent population in 1949 was estimated at 126,000, compared with 37,000 in 1940, and the transient winter population runs into thousands.

Pumping rates in Pima County rose from 80,000 acre-feet in 1940 to 129,500 acre-feet in 1945. Water levels in the vicinity of Tucson are reported by the United States Geological Survey to have dropped as much as 25 feet between 1940 and 1947 alone. Over 60 per cent more water was being pumped in 1945 than in 1941. About half the increase is attributable to the heavy draft by irrigation farmers. Water levels, once close to the surface, are now down as much as 300 feet in some places, and occasionally it has been necessary to drill down to 800 feet before obtaining an adequate supply.

Under present arrangements there is not enough water to meet all the requirements of urban and suburban residents, resort establishments, Southern Pacific Railroad shops, the University of Arizona (located in Tucson), and valley farmers. If present trends continue, Tucson may some day discover that its oasis has almost dried up (7).

The strenuous efforts that Los Angeles--the largest city west of the Mississippi River--has made in providing water for its residents indicate how closely this resource is tied in with municipal growth. Supplies are now obtained mostly from the Mono Basin (300 miles away) and the Owens River (238 miles away) in the Sierra Nevada, and from the Colorado River in Arizona. Without these sources of water, Los Angeles and the entire coastal region of Southern California would return to its natural state--that is, semi-arid desert. There is not a lake or a stream in the area below the mountains with a year-round flow. The search for usable water has been the preoccupation of the settlers since Spanish friars first established their missions in the eighteenth century (7).

Even the gigantic aqueduct from the Colorado River will be inadequate for the need in ten years or less. Consequently, today the people of Southern California are looking for another answer to their problem, a project which would bring them water from the Feather River which is more than 500 miles away (2).

Ground water is being withdrawn at the rate of 1.40 bgpd in the high plains of West Texas--30 times the rate of replenishment (6).

Northern New Jersey cities typify the kind of water problems found in Eastern seaboard communities. Around heavily industrialized Newark, supplied mostly by subsurface sources, wells have been drilled so closely together that water levels were seriously drawn down in 1947. Engineers report that there is grave danger that dependable yields have already been exceeded, and sharp diminishing of the supply is imminent. Seepage of salt water from the Passaic River and Newark Bay already made some wells practically useless (7).

Around Atlantic City the level of wells has dropped 100 feet below the former stationary depth, threatening an advance of salt water from the Atlantic Ocean even if consumption goes no higher.

No appreciable increase in the country's water supply is in sight, but the need increases steadily.

In 1950, the Geological Survey published an estimate of the total industrial withdrawal of water. At that time, the available data indicated a total private industrial withdrawal of about 77 bgpd, only slightly less than nationwide use of water for irrigation. In addition, approximately one-third to one-half of the water distributed by municipal systems serves industrial users (8).

The daily consumption of fresh water in the United States rose from 40 bgpd in 1900 to 203 bgpd in 1950, and it is expected to rise to 457 bgpd in 1975 (9).

The needs for industrial water estimated in the President's Materials Policy Commission Report are such that industrial use is expected to grow from 35 per cent of the total use in 1950 to 63 per cent of the total national requirements in 1975, despite increases in other uses. The Commission estimates that total water use will nearly double in the 25 years from 1950 to 1975 (8). If there are difficulties in certain locations over water use at present, they will certainly become greater as the nation's water requirement doubles.

Pressing needs for fresh water exist in the arid lands all over the earth. Many of these drylands were once centers of wealthy civilizations. Of the 35 billion acres of land on the earth, only 2.5 billion acres are under cultivation. The magnitude of the arid land problem is illustrated by the fact that about 6.4 billion acres are now too dry for cultivation. Thus arid lands constitute more than two and one-half times as much land as all of that currently under cultivation (10). In some arid countries, due to improved sanitation, the per capita consumption of water has suddenly risen from two or three quarts per day to 20 or 30 gallons or more (11).

Underdeveloped countries seeking to raise their standard of living by industrialization and irrigation find themselves with huge new needs for water supplies.

Israel could well exemplify this situation. Israel's efforts to reach economic self-sufficiency depend in great measure on the execution of its national water development program. Intensification of agriculture and the opening of the arid, but potentially fertile northern Negev, require the availability of increasing quantities of water.

Rain falls in Israel only during five months of the year, from November to April; the long summer is hot and dry. Rainfall varies from 42.5 inches yearly in the North to 0.8 inches at Eilat and in the South (12). Storage facilities must be built to conserve the surplus winter rain waters for use during the summer months. Storage facilities are also necessary to offset the effects of a drought, such as occurred in 1955. Israel's water sources include underground water, perennial springs, streams, flood water, and only one river.

To meet the ever increasing needs of agriculture, and to supply growing industrial and household needs at the same time, water consumption in Israel jumped from 6,600 mg in 1947 to 26,500 mg in 1955.

In ten years time from 1957 the quantity of water available per annum is planned to reach 47,500 mg (12, 13). A projection of the trend of increase in water consumption indicates that there will still not be enough available water to meet all consumption.

The situation is the same and even worse in many regions of the world, such as Iran, Iraq, Egypt, North Africa, and Italy.

There is no doubt that water supply problems will grow with the years, even in the most favored areas of the world. New uses are appearing, and the quantity needed is growing rapidly. Moreover, this demand is spot demand, and water resources of any locality, even with extensive storage, have an upper limit.

Thus one concludes that water shortages are reasonably certain to occur during the next two decades unless pains are taken to develop water sources that are of sufficient size and dependability to permit continuing growth, and to provide the necessary expansion.

The problem is the same the world over--civilization demands more and more fresh water.

Desalting sea or brackish water as a partial remedy.--The need for tremendous additional quantities of fresh water is established. This need is real and urgent. There are many ways of alleviating the situation, but no simple solution to the problem. The solution is indeed complex as is the problem itself, and depends strongly on locality. Water can be supplied to any land area and whether it is done or how it is done is a matter of cost.

Among the remedies, the conservation of existing supplies demands first consideration. Upstream management of water, which begins where the rain drop falls has long been recognized as having a significant part in the conservation of water. Much progress is possible in making more effective use of present water supplies through recycling and more efficient use. Pollution control, which merits much more attention than it has received, can vastly expand water supplies.

The most promising method for relief in semi-arid regions appears to be the development of techniques that would greatly reduce the total evaporation.

The obvious difficulty with rainfall is that it does not always fall when and where it is desired. Rain-making research is being conducted in an effort to alter the situation, but large land areas get their prevailing winds from colder regions and these provide moisture content far too low for adequate precipitation (14).

Within the context of accelerated water requirements and the several alternatives for increasing supply, the exciting prospect of desalting ocean and brackish water comes into focus. Conversion of salt water into fresh has been an ancient dream of mankind. Aristotle, in 350 B.C., described methods of extracting fresh water from the sea (5). Years later, Lord Francis Bacon observed that if sea water be heated to the boiling point, the salt will not vaporize and only fresh water will be distilled (16). The use of sea water on board ship is much more generally practiced than on land, primarily as the sea is the only available source of water.

One of the earliest recorded successful trials according to Hample (16) was that of Sir Richard Hawkins, the English Vice-Admiral who shared in defeating the Spanish Armada. Hawkins published in 1662, shortly before his death, the story of his voyage in 1593, to the South Seas in which he reveals that he used distillation to supply fresh water for his crew.

The subject of desalting sea water rose again about a century later when Boyle wrote an account of his experiments in this field, entitled "Saltiness of the Sea" (16). In 1684, the patentees, Robert Fitzgerald and several others, devised a still for use on ocean-going vessels. This design called for the addition of a "mixture" to sea water to achieve distillation (16).

The next notable work in this field was that by James Lind, Surgeon-in-charge, at the Royal Naval Hospital, Hasler, England.

Explaining his experiment he wrote: "to my great surprise the sea water distilled without any mixture added." (16)

In 1771, Dr. Irvine was presented a reward of 5000 pounds from the British Parliament for devising a successful distillation apparatus for use on board ship.

Thomas Jefferson (17), while Secretary of State, presented to the House of Representatives a report entitled, "Report on the Method for Obtaining Fresh Water from Salt." It is concerned with an investigation into a mixture which the inventor, Jacob Isssac, claimed would increase distillate. Jefferson writes, "On the whole, it was evident that Mr. Issacs' mixture produced no advantage either in the process or result of the distillation." (17)

With the advent of the steamship in the nineteenth century the practice of desalting sea water became nothing more than condensation of steam from the ship's boiler. The supplying of the English troops at Suakins and the Sudan in 1884 with fresh water was accomplished by this method (18). The practice, however, was abandoned when the increase in steam pressures and boiler sizes made the use of salt water hazardous both to safety and continuity of boiler operation (19).

Along with the practice of distillation, chemical desalting of sea water was introduced, originally for providing water for victims of sea disasters. In 1885 Kay demonstrated that four grains of citric acid plus 960 grains of citrate of silver would sufficiently demineralize a pint of sea water (20).

The practice of desalting sea or brackish (inland) water appeared much later on land than on the sea. However, in some areas need for fresh water on land as well as on the sea arose and in these areas distillation plants appeared.

A solar still, with approximately 51,000 sq ft of glass surface, was erected in 1872 at Salinas, Chile (21).

At the turn of the nineteenth century a multiple effect plant was tested in order to supply water for a naval station at Dry Tortugas, Florida, by a sugar apparatus manufacturing company of Philadelphia. The triple effect portion of the plant was built originally for concentration of sugar solution during the war with Spain (22). In 1917 the town of Stearns, Kentucky, began to use condensate from a coal mine power plant. This plant, condensing 50,000 gpd, furnished 40,000 gallons of water to the town (23).

Since World War II an increasing number of distillation plants for both inland and sea water usage have been built. A triple effect plant for Kuwait on the Persian Gulf was installed in 1949 with a capacity of about 700,000 gpd which has since been increased to 2.5 mgpd (24). Meanwhile a number of six effect units were constructed at Curacao in the Caribbean. This plant has a capacity of 400,000 gpd (21) which now has been increased to 1 mgpd (25).

The growing demands for more and more acceptable water, which are rapidly exhausting the natural sources, is recognized by the Congress of the United States. On July 3, 1952, the enactment of Public Law 448, 82nd Congress, 2nd Session, authorized the initiation of a Saline Water Research Program, under the United States Department of the Interior. The objective of the program is (26) "to co-ordinate and stimulate research and development of economically feasible processes by which saline waters of all kinds may be made useful for human consumption, municipal, industrial, irrigation, and livestock uses."

Meanwhile simultaneously, experimental work was undertaken in many other parts of the world by governmental agencies or interested individuals. To organize an International Symposium on Saline Water Conversion information was requested from thirty-one countries, not including the United States or the Union of Soviet Socialist Republics (27). Ten countries; Australia, France, Germany, Great Britain, Holland, Israel, Italy, Japan, South Africa, and Yugoslavia reported work in this field. This reveals world-wide interest on a subject which rightly merits such attention.

Many areas of the world will continue to get from conventional sources all the water they need in the foreseeable future, but at least for certain areas, ocean water, which covers three-fourths of the earth's surface, or sources of inland brackish water is the last frontier of plentiful water.

The composition of sea water has been the subject of various investigations. There is a high degree of uniformity between all the analyses. Armstrong (28) suggests the following for the composition of average sea water:

Table 1. Composition of Average Sea Water

| | Grams per kilogram | Pounds per thousand gallons | Mols. per liter | Gram Equivalent per liter |
|---|---|---|---|---|
| Cations | | | | |
| Sodium $Na^+$ | 10.722 | 91.6 | 0.4662 | 0.4662 |
| Magnesium $Mg^{++}$ | 1.297 | 11.1 | 0.0533 | 0.1067 |
| Calcium $Ca^{++}$ | 0.417 | 3.6 | 0.0104 | 0.0209 |
| Potassium $K^+$ | 0.382 | 3.3 | 0.0098 | 0.0098 |
| Total Cations | 12.818 | 109.6 | 0.5397 | 0.6036 |
| Anions | | | | |
| Chloride $Cl^-$ | 19.337 | 165.0 | 0.5435 | 0.5435 |
| Sulphate $SO_4^{--}$ | 2.705 | 23.1 | 0.0281 | 0.0564 |
| Bicarbonate $HCO^-$ | 0.097 | 0.8 | 0.0016 | 0.0016 |
| Carbonate $CO_3^{--}$ | 0.007 | 0.1 | 0.0001 | 0.0002 |
| Bromide $Br^-$ | 0.066 | 0.6 | 0.0008 | 0.0008 |
| Total Anions | 22.212 | 189.6 | 0.5759 | 0.6043 |

The pH of sea water is reported to be between 7.5 and 8.4, with a density of 1.0243 at 20 degrees C (29). To use this highly saline water the problem is to convert it to fresh. How pure the water has to be made is closely related to its application.

The taste of sodium chloride is recognized in water by most people at concentrations of 300 to 900 ppm. It becomes objectionable enough to curtail consumption of the water at concentrations of 1000 to 1500 ppm (30).

The non-toxic salts produce major physiological effects only when ingested at concentration materially above isotonic levels. At this concentration they produce dehydration of internal tissues, resulting in nausea and, if ingestion is continued, in the death of the organism. For sodium chloride the isotonic level is 7500 ppm, a concentration of 10,000 ppm induces vomiting (30, 19, 10, 31, 32). Drinking sea water also may affect the human mind. Azotemia may set in, which may be followed by irrationality, delirium, and suicidal tendencies (32).

In a few locations in the Southwestern United States, water containing a concentration as high as 4000 ppm of total dissolved solids is used continuously for drinking, although it is not desirable and is tolerated only through necessity (20). The United States Public Health Service requires that total solids should not exceed 500 ppm. However, if such water is not available, a total solid content of 1,000 ppm may be permitted. Simultaneously, the concentration of magnesium and chloride ions should be less than 250 ppm each (33).

Industries use water for many purposes and requirements as to the quality fluctuate widely. Although in most cases water supplies are adequate from the standpoint of quality (34), additional treatment is often required for industrial uses.

For use of water in irrigation it must be almost as good as drinking water. However, quality of the water for irrigation depends on a number of various factors, such as type of vegetation, composition of the soil, and rate of evaporation. Wilcox (35) suggests that a level of total solids exceeding 2,100 ppm is unsuitable for irrigation.

<u>Methods of conversion</u>.--Saline water is a relatively simple system of inorganic salt in water. As such, it possesses certain physical and chemical properties which determine the various phenomena by which the salt may be separated from the water.

Producing fresh water from salty or brackish water can be accomplished by several techniques: physical, electrical, chemical, biological, or any combination of these.

To accomplish the task by any of these techniques, energy must be supplied. This energy may be supplied from any conventional or nonconventional source. The combination of different techniques with different energy sources provides a long list of possibilities to desalt sea water.

Briefly, the following are possibilities (25):

I. PHYSICAL PROCESSES AND PHENOMENA

A. Vaporization

1. Vapor Compression Distillation
2. Single and Multiple Effect Evaporation
3. Flash Evaporation
4. Flash Type Multiple Effect
5. Combination Compression and Multiple Effect
6. Critical Pressure Devices
7. Super-Heated Steam
8. Temperature Differences
9. Solar Evaporation

B. Crystallization

1. Freezing of Water
2. Crystallization of Salts

C. Sublimation

D. Adsorption

1. Adsorption of Water
2. Adsorption of Ions

E. Diffusion Effects

F. Ultrasonics

G. Osmosis

1. Synthetic Membranes
2. Molecular Oil Films
3. Biological Membranes
4. Thermo-Osmosis

H. Immiscible Liquids

I. Combination Freezing and Evaporation

II. CHEMICAL PROCESSES

A. Ion Exchange

1. Synthetic Ion Exchange Resins
2. Natural Ion Exchange

B. Hydration

C. Precipitation

III. ELECTRICAL PROCESSES AND PHENOMENA

A. Electro-Ion-Migration

1. Electrolysis
2. Ion-Transfer
   a. General
   b. Selective
3. Electro-Gravitational

B. Streaming Potential

C. Electrostatic Effects

D. Electromagnetic Effects

E. Ultra High-Frequency Currents

Not all of these methods are practical, or in the foreseeable future could be used economically.

According to the United States' Secretary of Interior,

> Laboratory and economic study to date has narrowed the field from some twenty phenomena or processes to five broad groups: 1) Distillation through artificial heat; 2) Solar heat distillation; 3) Separation of salt by membrane, processes of two or possibly three kinds; 4) freezing; and 5) other chemical or electrical means of separation, including solvent extraction (25).

There are three variations of the distillation process that appear to have the most promise for low-cost conversion of sea water (36). The first is "multiple-stage distillation." It takes advantage of the fact that the boiling temperature of water increases considerably as the pressure is increased, so that the condensation of steam at one pressure may be used to supply heat for evaporation of water at a lower pressure. In practice the first stage water is evaporated at a given pressure. The vapor is led to a second compartment where additional water is evaporated at a lower temperature and pressure by use of the heat in the steam from the first stage. As the heat in the steam is given up to the water in the second stage, the steam condenses to give fresh water. The steam from this second stage furnishes heat for a third stage. In turn progressive evaporation of water is carried out in successive stages, each at a lower pressure and temperature. Theoretically this process can go on and on. Thus, one unit of heat in the first stage boils off many more units of water than in single-stage distillation. Construction of a one mgpd demonstration plant of this type by the Interior Department is approved by Congress. It is known as the long-tube-vertical multiple-effect distillation process which was developed jointly by the Office of Saline Water and the late W. L. Badger of Ann Arbor, Michigan. It is estimated that potable water can be produced in this new plant for less than $1.00 per 1,000 gallons (2).

Another distillation method of converting saline water to fresh water is "compression distillation." In compression distillation salt water is heated in a vessel until it boils. The steam that boils off is compressed slightly. This compression raises its temperature enough so that the steam can be used to boil additional salt water. As the steam gives up its heat to boil more salt water, it condenses to give fresh water. Once the process is in operation, the only energy required is the small amount needed to compress the steam.

In recent years the Badger Manufacturing Company, with Dr. K. C. D. Hickman as consultant, has designed and developed several rotary type vapor compression stills. These machines have developed heat transfer coefficients ranging from 2,000 to 3,500 BTU/hr/sq ft/°F (25). The cost of 1,000 gallons product by this process is estimated to be about $1.25 to $1.50 (37).

The third variation of the distillation process is called "flash distillation." In this process salt water is heated to a temperature below its boiling point and then admitted into a vacuum chamber. Part of the water evaporates or "flashes" into steam. The steam is condensed to furnish the fresh water. The advantages of flash distillation are that the water is not heated to a temperature high enough for scale to form on the heating surfaces and that rapid transfer of heat is possible with this scheme. Construction of a one mgpd demonstration plant by the Interior Department, employing this method has also been approved by Congress. This pilot plant is designed to utilize the heat from a low temperature, low pressure atomic reactor (2). The nuclear developed steam conversion plant is estimated to produce fresh water at between $0.50 to $0.75 per 1,000 gallons in multimillion gallon plant installation (38).

The present status of research and development work demonstrates conclusively that demineralization of saline waters by membranes is technically feasible and in some cases economical (39,40). Specifically, these processes consist of: 1) electrodialysis, in which an e.m.f. is applied to a cell consisting of ion-selective membranes; 2) reverse-osmosis, where sufficient pressure is applied to a solution to force water through an osmotic membrane into the fresh water side; 3) osmionic, where the concentration gradient between the solutions provides the potential to drive ions through ion-selective membranes; 4) transport depletion, a process which in its simplest form consists of zones or layers called controls (in which the transport numbers of ions are different from those in aqueous solution) interposed across the path of ions moving through an aqueous solution under the influence of a potential gradient. The concentration of the ionic components of the solution will be increased on one side of each interposed layer and decreased on the other side (25). 5) The possibility of desalting sea or brackish water by using biological membrane is also under investigation.

Levin (41) after a thorough study of the ion-transport phenomenon, a theoretical evaluation of the required energy for desalting salt water, concludes: "Physiological processes thus seem capable of operation at efficiencies far greater than those considered possible by mechanical, electrical, or chemical processes of saline water conversion."

Algae are suggested as a possible organism to extract salt from sea or brackish water. There exists considerable evidence that algae are capable of extracting potassium ion at a much higher rate than sodium ion. On the basis of this knowledge, Grune and the author (42) suggested a system in which the ion exchange bed combined with a culture of multicellular algae will accomplish the conversion. The sodium ion will be favorably exchanged for the potassium ion by ion exchange. Subsequently the algeal culture will remove potassium chloride from the water. Finally, the algae, rich in potassium salts, will be used in reverse cycle to recharge the ion exchange material. The feasibility of the process remains to be investigated.

With the exclusion of osmosis and reverse-osmosis, all membrane processes utilize ion-selective or permselective membranes. The membranes involved in osmosis or reverse-osmosis are often referred to as semi-permeable or osmotic membranes, and differ chemically and physically from the ion-selective membranes. Thus, all the membranes utilized in the various desalinization processes may be classified as ion-selective (permselective) membranes, or ion-restraining (ultrafiltering) membranes. The cost of water purified by the membrane processes embraces many factors such as the cost of membranes per unit area, equipment, energy operation, maintenance, and the salt concentration of raw water.

Membrane processes are distinctly different from other conversion techniques insofar as they remove the salt from the water rather than the water from the salt. These processes advantageously employ the chemical properties of saline water that all dissolved minerals exist in the ionic form. Consequently in these processes, the cost of demineralization is in direct proportion to the concentration of ions in solution. Therefore it is costly for sea water, but reasonably economical for brackish water. According to Jenkins and Powell (43), electrodialysis will produce 1,000 gallons of fresh water at a cost of between $0.80 and $1.00 if the raw water contains no more than 500 PPM of salt.

It may at first appear rather surprising, but freezing is another method of desalting water (44). A salt solution upon cooling will gradually deposit ice crystals, unless the initial salt concentration is very high in which case the dissolved salt will crystallize out of solution. Sea water, when cooled, freezes with the formation of pure ice and a residual more concentrated brine because of the removal of pure water in the form of ice (45, 46). The individual ice crystals are not contaminated with salt. The temperature at which ice begins to form is a function of the salt concentration, with lower temperatures required as the salt concentration is increased.

All experimental work with freezing as a means of separating salt and water have shown that the ice separated by filtration, draining, centrifuging, or other means still contains considerable salt; sometimes as much as one-half of the initial saline water concentration (47). Further efforts to reduce the salt concentration obviously add to process costs for producing sweet water.

Any freezing process must include partial freezing of a feed stream of saline water, followed by filtration or some equivalent operation to separate the ice from the unfrozen mother liquor. If ice were formed as very large pure crystals this separation operation would be simple, effective, and inexpensive. In reality, the situation is exactly the opposite, i. e., all existing processes produce only minute crystals, with a large proportion of entrained mother liquor and consequent difficulty of effecting sharp separation (45). The separation problem is increased by physical attraction between the mother liquor which is over 90 per cent water, and the surfaces of the ice crystals themselves, which are almost 100 per cent pure water. This inherent attraction distinguishes the saline ice washing problem from superficially similar industrial crystal washing operations in which the crystals are of an entirely different chemical nature than the mother liquor. Recently, a method for the removal of entrapped brine has been developed under the sponsorship of the Office of Saline Water in which the counter-current method of washing is utilized. This process, developed by the Carrier Corporation, appears highly promising. In addition to counter-current washing separation the technical feasibility of a process named zone-purification is also been studied (38). A preliminary estimate indicated costs in a range of \$3.00 to \$7.00 per 1,000 gallons. However, according to the Saline Water Report for 1958, it is foreseen that by good design, efficient operation, and low maintenance costs for freezing processes may ultimately be reduced to the order of \$0.50 to \$1.00 per 1,000 gallons.

Compared to evaporation, the freezing process has certain advantages in its application to separation of salts from water. Among these are its lesser tendency towards scaling and corrosion because of the low temperatures involved, and the potential economy due to the lower value of the heat of fusion as against the heat of vaporization. Perhaps a more significant advantage over evaporation is the opportunity for operation of freezing processes at low temperature differentials.

Among other processes of value to mention is solvent extraction (48). The application of solvent extraction in the laboratory and in the process industries has been increasing rapidly in recent years. Solvent systems are being developed which make the use of extraction theoretically attractive for effecting the separation of many compounds and products, and the appearance of mechanically agitated contacting devices has made possible efficiencies which are economically attractive. The first solvent extraction process for desalination of sea water was proposed for study by Hood and Harwell in 1952 (49), and was subsequently sponsored by the Office of Saline Water for investigation.

In the beginning emphasis was placed on the search for more efficient compounds and operation of a laboratory model, particularly on brackish waters. The next step in the process development will be the design, construction, and testing of a small pilot plant for brackish water treatment (38).

There are two approaches to the solvent extraction method for desalination: first, that of removal of salt from water; and second, removal of water from salt. The first of these is not promising, since a solvent capable of removing salt from water would probably be more difficult to separate from the salt than was the water from the salt initially. Certain advantages might be realized for salt-solvent over salt-water separation in specific instances; however, no substance is known which dissolves the salt of sea water in quantities and which is not miscible with water.

The second method, that of extracting water away from salt, has considerably more promise. However, the objection has been that the mixing of water with solvent would be accompanied by an increase in entropy; otherwise it would not take place and that, therefore, this method is theoretically less efficient than the others. This ignores the fact that all processes involve irreversibilities, and that it is possible to devise reversible extraction as well as reversible heat transfer. If reversibility could be devised, the energy consumption for all processes would be identical. Furthermore, the partial miscibility of the water and solvent offers a method of easily effecting separation if the degree of miscibility is sensitive to temperature.

Solar distillation processes will be thoroughly discussed in the next section.

Examination of the results of various investigations reveals that each process is suitable only under certain conditions. A process which may not be feasible or economical under one set of conditions may lend itself to be the answer under a different set of circumstances (25).

Solar distillation.--The need for additional sources of energy was clearly brought out at the Geneva Conference on Atoms for Peace (50) in August 1955. The conference stressed clearly that our fossil fuels, coal, oil, and gas are distinctly limited. In relatively fuel-rich United States, the problem may become acute for our grandchildren but some other countries are feeling the pinch of a decrease in high-grade, easily mineable coal right now. Moreover, the world's population is increasing rapidly and the demands for abundant energy are increasing still faster.

The world looks to the atom to supply the bulk of the energy requirements of tomorrow, thanks to the foresighted genius and diligence of the world's scientific community. However, atomic energy alone cannot solve our problems. The development of economical power reactors is complex, vastly expensive and relies on highly developed scientific and industrial processes and advanced production techniques. Atomic energy production will come probably in multi-million dollar central power-stations near large cities and towns.

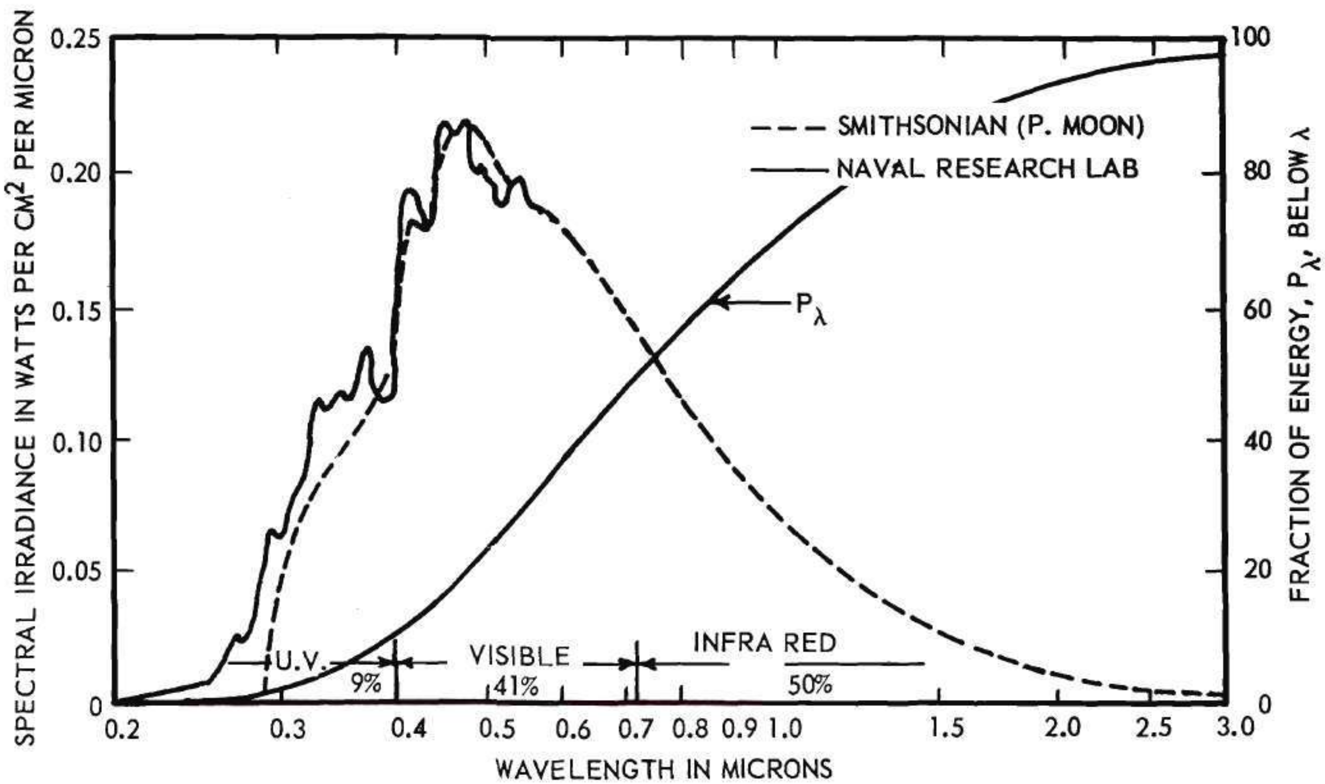
The world's constantly rising need for energy and the tremendous supplies available directly from the sun suggest the possibility of harnessing this free, everlasting source for raising the comfort and enjoyment of mankind. Unlike atomic energy, solar energy has no critical mass, presents no health hazards (except sunburn) and creates no waste products which must be disposed of. Unlike atomic energy, the utilization of solar energy is expected to start with smaller units. Solar batteries, heating, and distillation units will find their first small-scale practical applications in rural and non-industrialized areas.

The total energy of the sun falling on the earth is far more than is needed to do the world's work. To carry on the energy-rich civilization of the United States, in 1952 this country consumed 164,000 kilocalories of fuel energy or 186 kilowatt hours of heat energy per person per day. In 1952 the per capita consumption of fuel by all the people of the world was 24,300 kilocalories per day. By comparison the total energy from the sun striking the land area of the United States is of the order of 270 million kilocalories, or 313,000 kilowatt hours, per person per day (51). Theoretically, the available supply far exceeds the need; however, it is only available in the form of low temperature heat which is difficult to convert economically into work, and difficult to store or to transport.

The average amount of solar energy which reaches the outer limits of the earth's atmosphere is known accurately within a few per cent. On a surface perpendicular to the sun's rays it is on the average about two ly/min* or about 440 BTU/sq ft/hr. On the average for the whole earth, a unit horizontal surface outside the atmosphere will receive one-half of this energy during the daylight hours (52). The sun energy on a perpendicular surface is distributed spectrally as shown in Fig. 1. The fraction of the total energy which lies below a given wave length is also shown. For example, the energy in the ultraviolet range below $0.4\mu$

*one langley(ly) = 1 gram - cal/cm$^2$ = 3.69 BTU/sq ft

DISTRIBUTION OF SOLAR ENERGY VS. WAVE LENGTH




Reported from Fritz, S. "Transmission of Solar Energy through the Earth's Clear and Cloudy Atmosphere", Transaction of the Conference on the use of Solar Energy, University of Arizona Press, Tucsun, Arizona, 1958

Figure 1.

Distribution of Solar Energy vs. Wave Length comprises about 9 per cent of the total incident energy, in the visible range (which contains the peak 0.46μ) is the energy 41 per cent, and the infrared range, beyond 0.72 μ, contains about 50 per cent of the incident energy (52).

As solar energy enters the atmosphere of the earth and travels downward it goes under depletion. X-rays and other very short wavelength rays are absorbed very high in the ionisphere by oxygen, nitrogen, and other atmospheric constituents. Somewhat longer wavelength rays are absorbed by ozone. There is rarely more than 0.4 centimeter of ozone in a vertical column of the atmosphere, concentrated mainly at elevations between 15-35 kilometers; yet the absorption coefficients in ozone are so large that the spectrum of solar energy at the ground is cut off below 0.29μ (53).

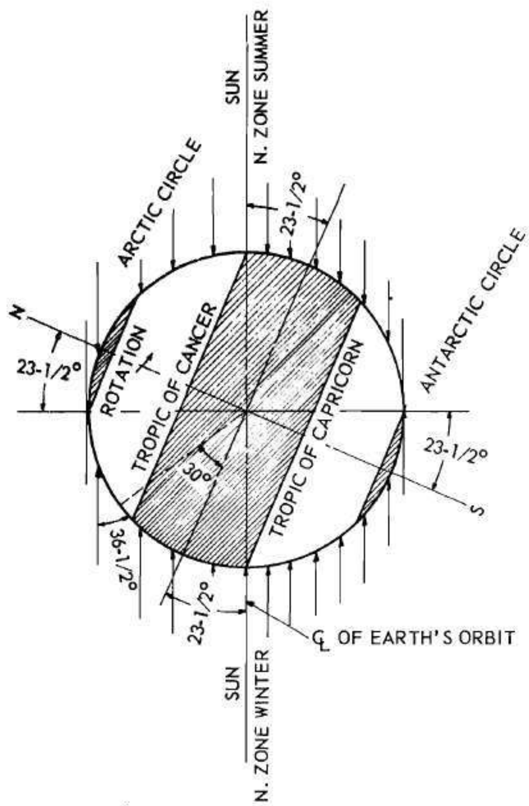
Therefore, from the viewpoint of utilization of solar energy near the ground, attention needs to be focused only on wavelengths longer than 0.29μ. As the remaining solar energy proceeds through the atmosphere, it may undergo two principal variations. It may be scattered or absorbed. Scattering may be accomplished by molecules, by dust or other atmospheric impurities, and by water particles. Small amounts of many substances absorb solar energy, but the principal absorbing media are ozone, water vapor, and water droplets.

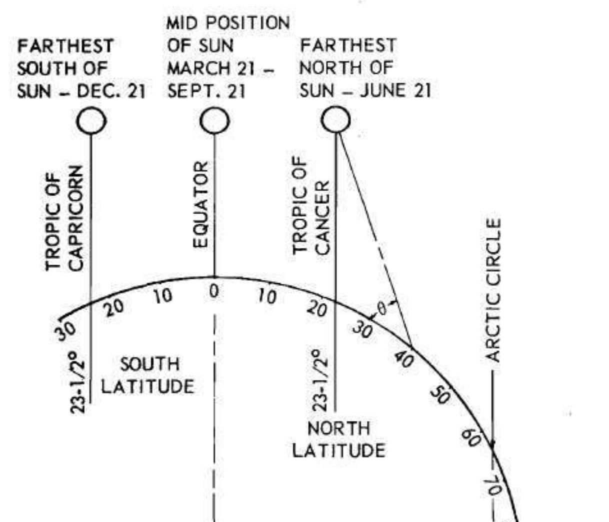
In brief, about 19 per cent is absorbed by the clear and cloudy atmosphere. Another 35 per cent of the energy intercepted by the Planet Earth is immediately reflected to space. Thus only about 46 per cent of the extraterrestrial energy reaches the earth's surface (52). These numbers are averages for the entire solar spectrum and for the whole earth. These reflections and absorptions are, however, not uniform at all wavelengths in the spectrum. Also important variations from these averages will be introduced by astronomical considerations, such as latitude and season.

The sun moves daily from the eastern to the western horizons and annually from the farthest north to the farthest south positions. Fig. 2 shows the relation of the earth to the sun's rays in both winter and summer for the northern hemisphere, where it will be noted that the sun's rays fall vertically on the Tropic of Cancer when the sun is farthest north, and vertically on the Tropic of Capricorn when the sun is farthest south. It may also be noted that the summer period in the northern hemisphere, at the time when the sun is perpendicular over the Tropic of Cancer, the sun's rays are tangent 23 1/2 degrees past the North Pole, or at the far side of the Arctic Circle, while in the winter period when the sun is farthest south, the rays are tangent 23 1/2 degrees from the North Pole, or at the near side of the Arctic Circle (54).

It is obvious that if the total number of the sun's rays falling vertically on a square foot of surface is considered as unity, the proportional number of the sun's rays falling on the same square foot at an angle will vary as the sine of that angle. On the basis of this statement it is possible to draw a curve which shows the changes of sun's rays as a function of degree of inclination of the sun. Fig. 3 represents such a curve (54). To find the angle with the horizontal at which the sun's rays strike the earth at noon on any particular date, the following formula may be used:

SEASONAL VARIATION OF SUN POSITION RELATIVE TO EARTH



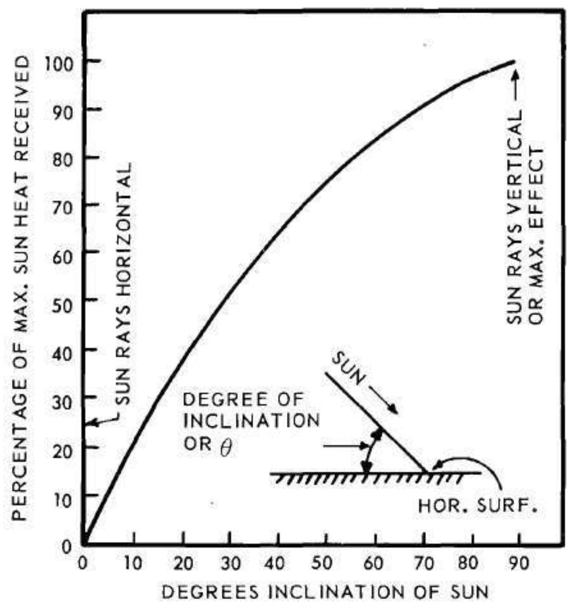

Reported from, Alt., H. L., "Sun Effect and the Design of Solar Heaters", Heating Piping and Air Conditioning, Vo. 7, pp. 111–118, Feb., 1935

Figure 2.

Seasonal Variation of Sun Position Relative to Earth

PERCENTAGE OF ENERGY RECEIVED AT DIFFERENT ANGLE OF INCLINATION

(On the Basis of Sun Rays Vertical)




Reported from, Alt., H. L., "Sun Effect and the Design of Solar Heaters", Heating Piping and Air Conditioning, Vol. 7, pp. 111–118, Feb., 1935

Figure 3.

**Percentage of Energy Received at Different Angle of Inclination**

OBSERVATIONS OF SOLAR RADIATION AT POTSDAM, GERMANY, B.t.u. FT.$^{-2}$ H.$^{-1}$

| | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| JAN | | | | | 172 | 260 | 288 | 297 | 298 | 276 | 252 | 175 | | | | |
| FEB | | | | 110 | 222 | 260 | 273 | 280 | 276 | 273 | 260 | 222 | 110 | | | |
| MAR | | | 70 | 180 | 237 | 264 | 280 | 283 | 283 | 280 | 255 | 225 | 170 | 70 | | |
| APR | | 89 | 160 | 222 | 255 | 276 | 290 | 292 | 295 | 292 | 280 | 252 | 220 | 160 | 86 | |
| MAY | 45 | 116 | 208 | 248 | 268 | 283 | 292 | 295 | 295 | 292 | 280 | 264 | 237 | 198 | 110 | 45 |
| JUN | 70 | 150 | 208 | 240 | 264 | 280 | 288 | 292 | 292 | 288 | 276 | 255 | 232 | 201 | 142 | 60 |
| JUL | 45 | 140 | 204 | 234 | 260 | 276 | 288 | 290 | 292 | 283 | 273 | 252 | 228 | 198 | 134 | 45 |
| AUG | | 100 | 170 | 240 | 271 | 288 | 297 | 297 | 301 | 297 | 283 | 252 | 215 | 164 | 95 | |
| SEPT | | | 130 | 240 | 280 | 295 | 301 | 318 | 301 | 288 | 290 | 248 | 201 | 113 | | |
| OCT | | | | 196 | 264 | 295 | 303 | 311 | 311 | 297 | 292 | 264 | 175 | | | |
| NOV | | | | | 208 | 264 | 288 | 292 | 292 | 288 | 271 | 206 | | | | |
| DEC | | | | | 110 | 248 | 276 | 288 | 283 | 271 | 237 | 110 | | | | |

Reproduced from Groundwater, I.S., "Solar Radiation In Air Conditioning", Crosby Lockwood & Son, Ltd., London, 1957

Figure 4.

**Observations of Solar Radiation at Potsdam, Germany, B.t.u. Ft.$^{-2}$H.$^{-1}$**

$$\theta^\circ = 90^\circ - (\text{latitude of place} - \text{latitude of sun}) \tag{1}$$

which formula applies for all conditions with the sun north of the equator but which must be modified when the sun is south of the equator to:

$$\theta^\circ = 90^\circ - (\text{latitude of place} + \text{latitude of sun}) \tag{2}$$

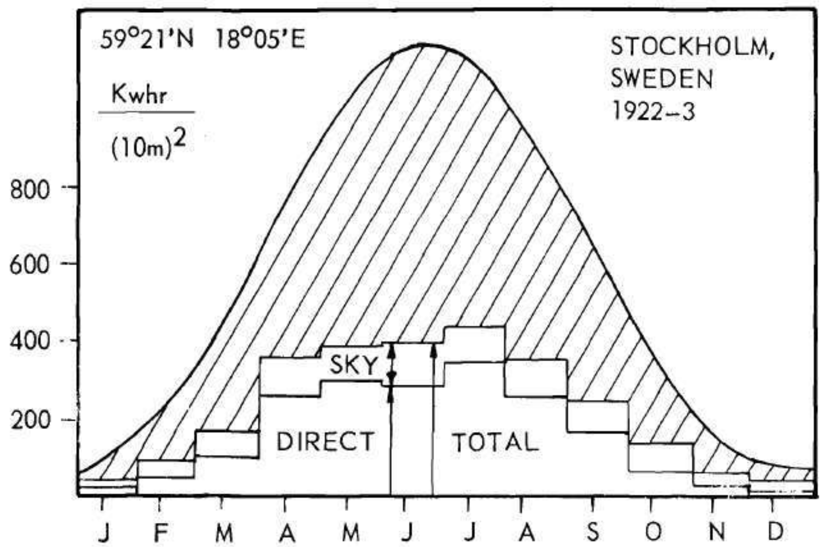
The intensities of the sun's rays with the horizontal earth's surface is the sum of the intensities of: a) direct solar radiation, and b) indirect solar radiation, diffuse radiation or sky radiation.

Direct solar radiation is apparent in the sunbeam. It is that fraction of the solar constant which has survived the water-vapor ambushes in the atmosphere and eventually reaches the earth's surface. Indirect solar radiation, the other fraction of the solar constant, is absorbed and then a fraction of it reradiated downward from the water vapor in the various atmospheric layers. Fig. 4 shows the observations of direct radiation throughout the year for a typical station in Europe (55). This graph is selected because it shows clearly the variation of solar energy with time. The line dividing the shaded from the white area represents sunrise in one case and sunset for the other. This presentation of the data shows the hourly variation for each month of the year, and the monthly variation for each hour of the day. Maximum values occur during the summer months, (according to the observations) though noon values in winter and summer are much the same, indicating that the effect of the varying solar distance is negligible. Excluding noon values, there is a steady increase in solar insolation intensity values as the summer approaches and a steady fall as winter approaches.

Fig. 5 shows the comparison of monthly direct and sky radiation for Stockholm, Sweden. Values on the boundary line between the white and the single shaded areas represent the primary supply of solar radiation in the course of the year at the outer edge of the atmosphere over Stockholm. The angle of incidence of the sun's beam with the outer envelope of the atmosphere varies throughout the year with the sun's declination, describing the curve shown. The single shaded area represents that part of the original energy input which is lost by re-radiation back to space. The upper line is drawn for the monthly average of direct and sky radiation received. The lower line is drawn for the monthly average of simultaneous direct radiation. The area enclosed, constituting the difference between the total radiation and the direct, represents the sky radiation. It is of interest that during July the sky radiation is approximately 20 per cent of the total, while during the winter it varies from 60 to 80 per cent of the total (55). From the standpoint of utilization of solar energy, it is necessary to know the actual amount which reaches the surface of earth and is available. Such values are shown (56) for a number of select stations in the Table 2.

Because of the difference in wavelength between solar radiation and thermal radiation from a heated body, it is possible to construct an energy trap which allows the short wave solar radiation transported into the trap but opaque to the long wave thermal radiation from the collector plate. The collected energy can then be utilized advantageously by converting it to another kind of energy or using it directly as heat to demineralize saline water.

CURVE OF DAILY TOTALS OF SOLAR RADIATION ON A HORIZONTAL SURFACE AS MEASURED ON ÅNGSTRÖM'S PYRANOMETER




Reproduced from Groundwater, I.S., "Solar Radiation In Air Conditioning", Crosby Lockwood & Son, Ltd., London, 1957

Figure 5.
**Curve of Daily Totals of Solar Radiation on a Horizontal Surface as Measured on Ångstrom's Pyranometer**

Table 2. Average Solar Radiation at Selected Stations*

| Location | Horizontal surface Min. Month | Horizontal surface Max. Month | Horizontal surface Year Ave. | Surface tilted toward equator, angle = latitude Year Ave. |
|---|---|---|---|---|
| Algeria (Tamamassit | 1460 | 2400 | 2000 | 2130 |
| Argentina (Buenos Aires) | 765 | 2650 | 1580 | 1962 |
| Australia (N. S. Wales) | 757 | 2350 | 1575 | 1835 |
| England (London) | 181 | 1740 | 882 | 1210 |
| India (Poona) | 1430 | 2690 | 1980 | 2080 |
| Japan (Mito) | 1055 | 2170 | 1705 | 2100 |
| Un. So. Africa (Messina) | 1340 | 2320 | 1875 | 1985 |
| Puerto Rico (San Juan) | 1528 | 2280 | 1940 | 2000 |
| U. S. A. Swan Island (W. I.) | 1450 | 2390 | 1985 | 2050 |
| Honolulu T. H. | 1395 | 2380 | 1930 | 2040 |
| El Paso, Texas | 1200 | 2730 | 2030 | 2310 |
| Fresno, Calif. | 610 | 2620 | 1660 | 1920 |
| Miami, Fla. | 1070 | 1845 | 1512 | 1650 |
| Stillwater, Okla. | 775 | 2205 | 1460 | 1752 |
| Blue Hill, Mass. | 502 | 1938 | 1240 | 1590 |
| Madison, Wis. | 406 | 2030 | 1210 | 1530 |
| | Dec. | June | Year Ave. | |
| Riverside, Calif. | 782 | 2207 | 1558 | |
| Santa Maria, Calif. | 867 | 2399 | 1817 | |
| Albuquerque, N. Mex. | 1085 | 2749 | 1892 | |
| Las Vegas, Nev. | 845 | 2771 | 1822 | |
| Salt Lake City, Utah | 443 | 2192 | 1442 | |
| Phoenix, Ariz. | 1061 | 2710 | 1925 | |

*All values in BTU/sq ft/day.

Solar radiation could be converted to electrical power and then used in various ways to desalt sea water. Methods include refrigeration, photosynthesis, photochemistry, and thermoelectric conversions through utilization of the solar energy; all appear highly attractive. However, these processes have not yet been completely investigated and their applications still depend on the prior solution of many practical problems.

The machine which utilizes the trapped energy of the sun to convert saline water to fresh, through evaporation and condensation processes, is called the "solar still." Solar stills are of two kinds: 1) high temperature distillers, and 2) low temperature distillers. The first kind belongs to the class of collector-concentrator for production of vapor. After performing work the vapor will condense and provide fresh water, or it may be used in a conventional distillation equipment, such as multiple-effect evaporator or vapor compression type design. The second type of still are those which combine collector-evaporator system within a single unit. Such a unit usually includes the condensing surface too.

Many devices have been proposed and examined including those in which solar energy is focused to make available high level thermal energy at a designated point (57). Lof (56) traced the successful operation of such designs to the nineteenth century and provides a rather complete bibliography. A multiple-effect evaporation system, using steam generated in solar collectors of the parabolic, cylindrical type, was studied by Battelle Memorial Institute under contract with the Office of Saline Water (58). The report of their studies confirm the fact that the process is practical and feasible, but expensive. Löf (56) and Strobel (59) contributed the principal reason that these experiments have not been pushed to development and application due to the high cost of equipment. The polished reflector surfaces, their mounts, and tilting mechanisms all are extremely expensive. Another problem of solar energy concentration constitutes an inherent disadvantage of this type of collector. Only the direct part of the solar beam can be focused by reflectors, the diffused or sky radiation is ineffective. The loss accounts for at least 10 per cent radiation even on exceptionally clear days.

Solar stills without energy concentration devices have been extensively studied by numerous investigators the world over (56 - 67). At least one large plant of this type has been operating since 1872. This plant, erected at Salinas, Chile, is 4300 feet above sea level, and has 51,200 square feet of glass arranged in sections 4 feet wide and in the form of an inverted V, forming the roof of a shallow water trough. The sun evaporates the water and the resulting vapor condenses on the glass, for the temperature in the box is higher than that of atmosphere and hence of the glass. The pure water trickles down the sloping glass and drips from its lower edge into a small channel on the top of each side of the box. These channels deliver into larger ones and thus the distillate is collected. According to Harding (68), distillation starts at 10 a.m. and continues to 10 p.m.

Numerous designs, ranging from very complicated ones to one with only minor refinement of this principal design have been proposed and some have been studied in detail. Löf (56) has theoretically analyzed some 30 proposed methods and also suggests several other designs for demineralization of saline water with solar energy. Their review shows the extensiveness of devices that have been envisioned and studied. Among all these many designs, Löf concludes cautiously that the simple, direct solar-heated evaporating trays with self-contained condensers, similar to the one in Chile, appear to be the most economical.

The most important designs which have been recently subjected to experimental analysis will be briefly discussed to illuminate the present status of art and science of solar distillation. The first of these is illustrated by the sketch shown in Fig. 6 and Fig. 7. This "conventional" design is very similar to the Chilean type, already discussed. A 200 sq.ft prototype plant, designed by M. Telkes (64), has been operating at Cohasset, Massachusetts, since the summer of 1951. A modification of this design was proposed by R. E. Glover who suggested the "deep-basin" still. The deep-basin design, Fig. 8 and Fig. 9, permits a considerably deeper layer of water in the basin (one foot rather than the usual one or two). A critical study and theoretical evaluation of this design was published by Löf (69, 70). Subsequent to his study, Löf further modified the deep-basin design.

The deep-basin which was designed by Löf differs from the conventional type still in that it omits the insulation around the bottom of the still. It is designed directly on the ground, of concrete, or other permanent materials. A pilot plant of this design was recently constructed by the Battelle Memorial Institute at the Experimental Station at Port Orange, Florida, under the auspices of the Office of Saline Water, Department of Interior, and is expected to provide basic data which will result in engineering specifications and design.

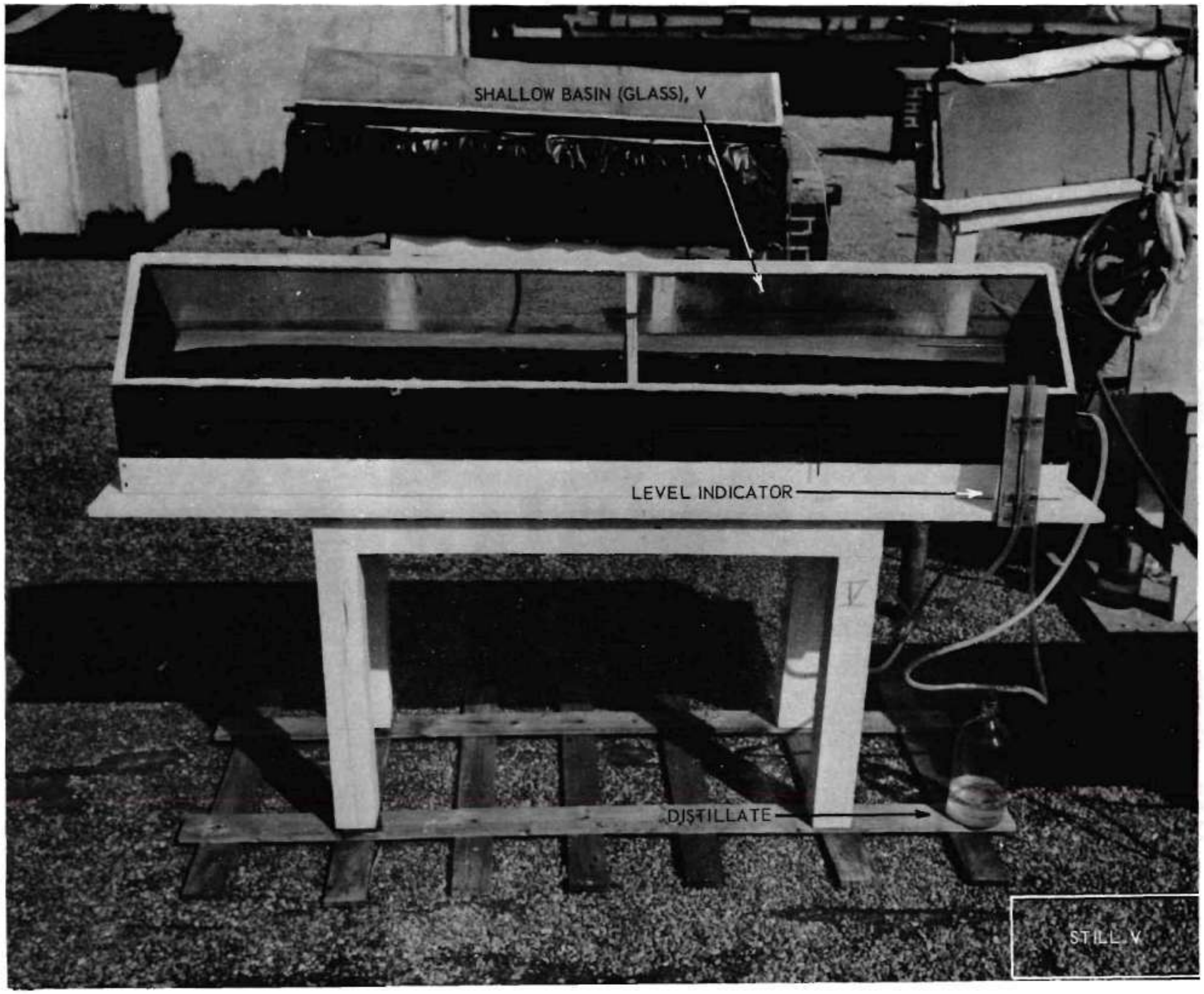
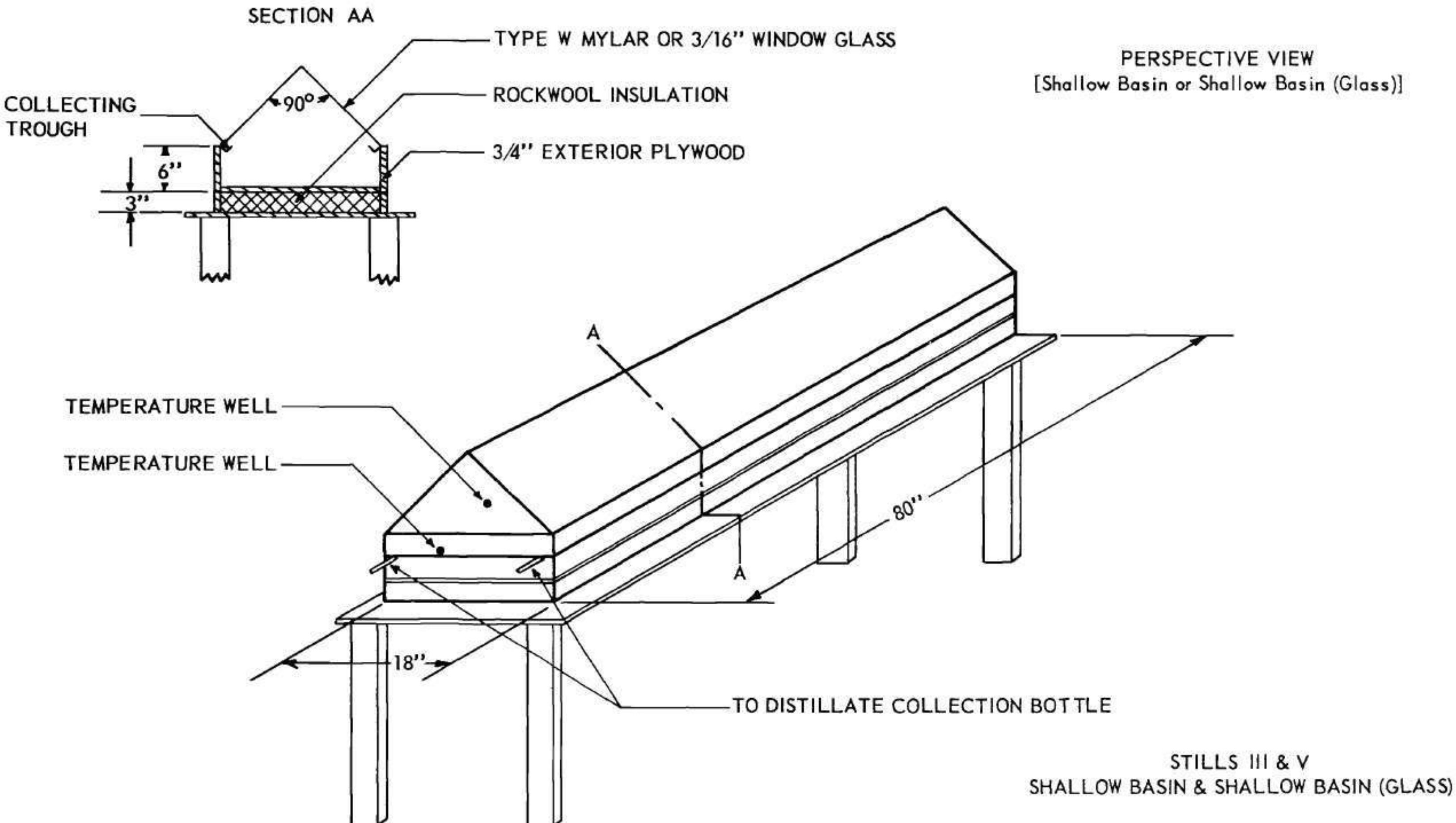



Figure 6.
**Shallow Basin (Glass)**




STILLS III & V
SHALLOW BASIN & SHALLOW BASIN (GLASS)

ALL PLYWOOD IS 3/4" 5-PLY EXTERIOR

MYLAR PLASTIC IS 0.005" THICK

ALL SEALING IS DONE WITH CAULKING COMPOUND

2" x 2" "L" BRACKETS WITH STOVE BOLTS HOLD THE BASIN COVER IN PLACE

Figure 7.
Perspective View [Shallow Basin or Shallow Basin (Glass)]

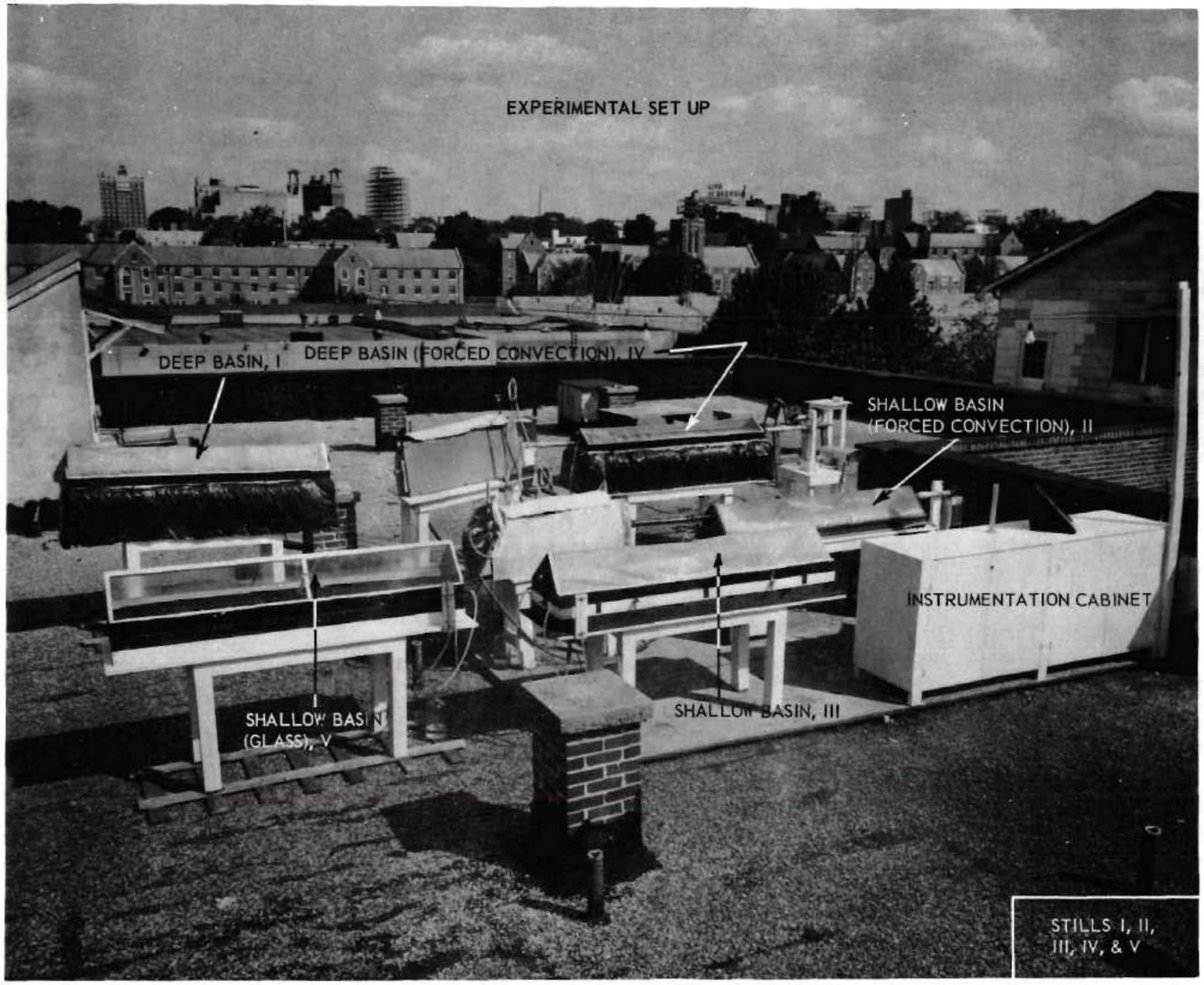



Figure 8.
**Experimental Set-Up**

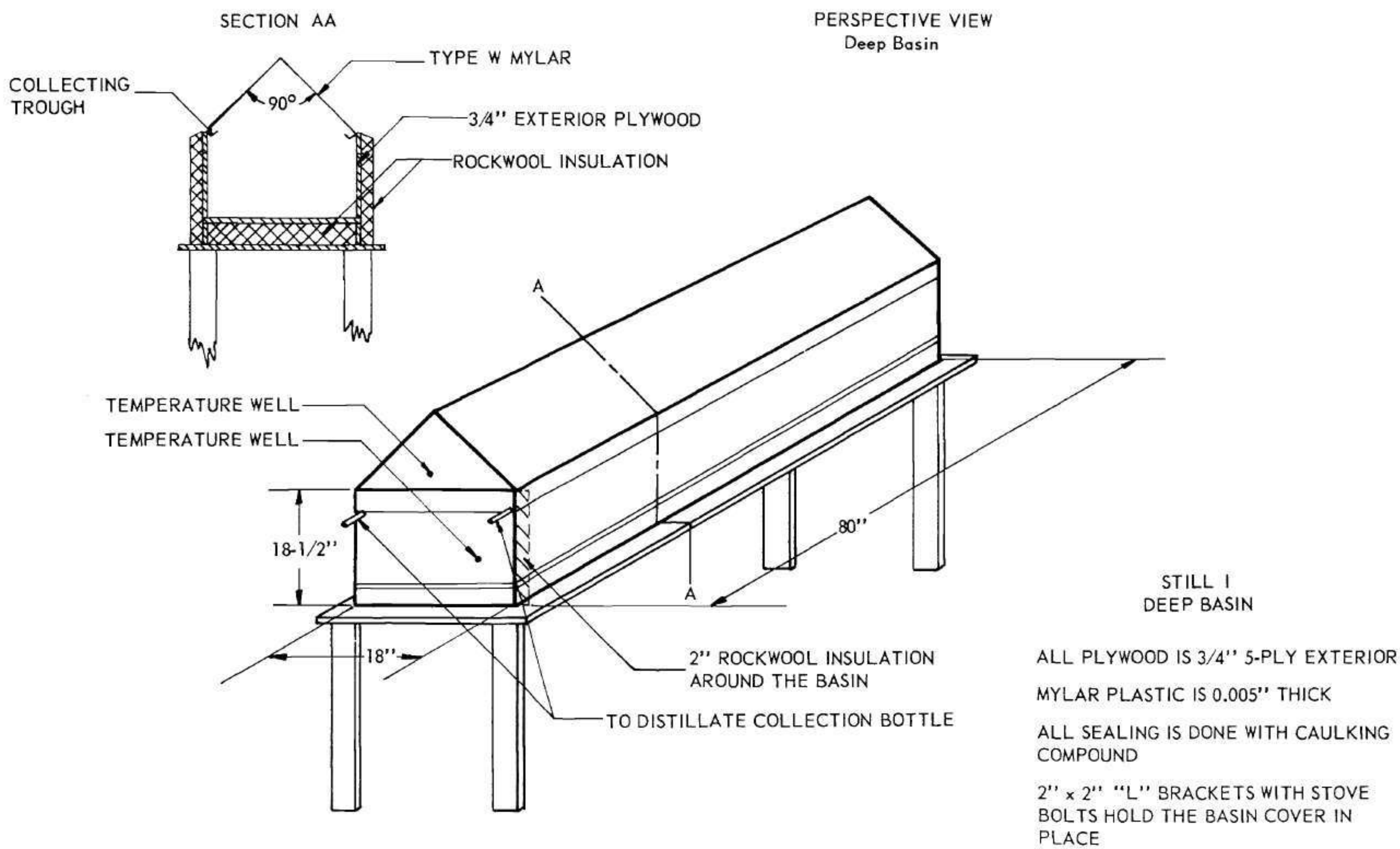



Figure 9.
**Perspective View (Deep Basin)**

An additional modification of the basic design suggests the utilization of transparent materials for the roof in lieu of the glass roof. Several investigators have studied this type of still roof construction (60, 63, 71). An investigation by Bjorksten Research Laboratories Inc.*, has demonstrated that by proper selection and treatment of plastic surface materials, it is possible to construct plastic solar stills with an efficiency up to 92 per cent of those with identically designed glass roof stills. The roof covering material cost of such plastic stills is only 10 to 25 per cent of the costs of similar glass stills (71). The economy realized because of lower installation, transportation, and maintenance costs for plastic solar still helps to provide an inexpensive means of producing fresh water from large-scale solar distillation.

To obtain information on the permanence of plastic films when exposed to weathering and concurrent moisture, the following films were exposed to atmospheric conditions by the Bjorksten Research Laboratories:

Polyvinyl chloride, 4-mil (two types)
Polyvinyl chloride, 8-mil (two types)
Double vinylidene chloride-vinyl chloride copolymer, 5-mil
Polyvinyl chloride, 6-mil
"Griffolyn," polyvinyl chloride reinforced with grid of polyester threads, 1-mil over-all thickness
Polyester, 1/2-mil
Polyester, 1-mil

At the Florida exposure site, a sample of each type of film was stretched under moderate tension over the top of a metal drum and held in place by means of a "hoop" of coiled spring. Each drum was slanted about 15 degrees from the horizontal, facing south. Water vapor from the hot, wet sand, "wet with sea water and densely colored black with a household dye" (71), condensed on the inside surface of the film and ran back down,

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*Madison, Wisconsin.

thus providing a situation similar to that encountered during distillation in solar stills. Mere exposure of films in frames however does not provide comparable results. After a field exposure of four months, the polyethylene and polyester films had deteriorated; all of the other films appeared to be in good condition. However, at the end of six months, the portion that was exposed to moisture and direct sunlight had become embrittled in all films except the double vinylidene chloride-vinyl chloride copolymer. This film remained in good condition, but had darkened to the extent that the outer layer was almost opaque (71).

An air-supported, plastic canopy is under experimentation by E. I. du Pont de Nemours & Company Inc.* in a pilot plant constructed and now under investigation at Port Orange Station. In this design, a black polyethylene sheet material is laid directly on inexpensive insulating material, placed on the ground, to form an evaporation pan. Transparent plastic films of Teslar and Mylar, supported by slight air pressure, are used for the cover and condensing surface.

There are several factors that seem to mitigate against the use of plastics in solar stills. Among these are: 1) poor wettability of these films, 2) deterioration of plastic film in direct sunlight. Still needed, to quote the 1956 Annual Report on Saline Water Conversion, is a "thin plastic film which is tough, wettable, with high transmission properties, and with excellent resistance to weathering" (72).

All prototype stills discussed receive solar radiation on a horizontal surface. A number of tilted solar stills have been designed and investigated first by M. Telkes and followed by others (73, 64, 7, 74).

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*Wilmington, Delaware.

A roof-type solar still could be tilted by changing the water tray over into a porous pad, fed continuously with sea water at one end and equipped with a brine-collecting channel at the other end. The still, supported by its stand, is faced to the south. It is tilted at the angle that intercepts the highest intensity of solar radiation. This tilting increases the amount of solar energy received at various different latitudes.

Still another design investigated by M. Telkes (74) is a multiple-effect type of solar still which was suggested years ago by Ginning (56). The multiple-effect still consists of parallel layers mounted on water-proof frames, stacked like the frames in a filter press. Water-impervious films are tightly mounted over the frames. Porous, thin layers are laminated to both sides of this film (or on the evaporator side alone, if the film is water wettable). Saline water is fed to the top of the film in an even, continuous layer through a distributing channel. On the bottom edge of the frame, brine and distillate are collected separately in channels. Variations of this basic design was also suggested by several other investigators. An improved design of this type was worked out at the University of California, Los Angeles (75).

Table 3 shows the reported yield of different designs on the basis of lb/sq ft of still area.

Table 3. Summary of Experimental Results

of Conventional Solar Still

| Reported by | Location | Mean Daily Solar Radiation BTU/sq ft/day | Distillate lb/sq ft/day Max. | Avg. |
|---|---|---|---|---|
| Wilson, B. W. | Mildura, Australia | 2656 | ___* | 0.96 |
| | | 2361 | ___ | 0.77 |
| | | 1861 | ___ | 0.45 |
| | Melbourne, Australia | 2317 | ___ | 0.95 |
| Nebbia, G. | Bologna, Italy | 1800 | 0.5 | ___ |
| Howe, E. D. | Berkeley, California | ___ | 0.84 | ___ |
| Bjorksten Research Laboratories | Madison, Wisconsin | ___ | 0.86 | ___ |

*Is not reported.

# CHAPTER III

## DELINEATION OF THE PROBLEM

Fundamental considerations of solar distillation.--Salt water differs from fresh water thermodynamically due to the free energy of dilution of the dissolved salt. The deionization of water involves the reversal of a natural diffusion process, which is accompanied by an increase in entropy. This process can only be reversed by a process which involves a compensating increase in entropy in some other form or manner.

A clean-cut separation of pure water* from salt solution may be obtained by change of phase. Pure water is removed from the interface of surface of the solution as vapor or ice. The ions concentrate at the surface or interface and move back into the solution under a natural diffusion gradient. The entropy increase that must compensate for this process is transferred to the system by the transfer of heat. But heat flow requires a thermal gradient, which must be considerable if the process is not to be too slow or the equipment not too massive. The objection to massive equipment is the high initial cost and the heavy maintenance expense.

The work of removal of one mole of water in the pure state from a large amount of brine is given (76) by the expression:

$$U = RT \ln \frac{P}{P_o} \qquad (3)$$

*Pure water is considered here as water with a resistance of more than 100,000$\Omega$ or defined as having less than 500 PPM total solid for drinking water or 2100 PPM total solid for agriculture.

An isothermal process is assumed. No concern is given to the quantities of heat that must be transferred in any actual process. This simply represents the minimum work that must be supplied by any process of separation. Any actual process may exceed this required amount because of thermodynamic inefficiency. At 25°C the vapor pressure of sea water with a salt content of 64090 PPM is 23.238 mm and of pure water is 23.756 mm. Therefore, according to formula (3), the minimum work which must be supplied in order to have 18 grams (one mole) of fresh water from a salt solution at 25° is about 13.05 gram cal. This is equivalent to $2.750 \times 10^{6}$ gram cal or 2.89 KWH per 1000 gallons of fresh water. It is, therefore, never expected to find a purification process requiring below 2.89 KWH per 1000 gallons of fresh water. Furthermore, in actual practice such a low energy requirement is aspired but can never be reached. For example, in unit processes, such as evaporation, a great deal of work must be expended to overcome the mutual attractions of the water molecules. Another important reason for extra energy input is the need for the water to seep through the surface interphase fast enough to achieve a certain amount of output without the installation of a truly great size, thus the energy investment must always be much greater than the basic minimum already discussed.

The principal advantage of the distillation method is that the energy supplied to the evaporator can be in the form of heat directly applied from the source. This advantage is further appreciated if it is considered that heat is a low grade source of energy, and can never be converted 100 per cent into useful work. The best diesel engines are around 35 per cent efficient in converting the energy of burning fuel into useful work. In solar distillation the required energy is supplied by radiation from the sun. For most purposes solar energy can be thought of as light near the earth's surface having the properties as discussed in Chapter II.

If we try to describe a bundle of wave energy of light, we encounter one of the most interesting aspects of modern physics. This is, light can behave as an electromagnetic wave or as a stream of material particles. The best picture for describing light in terms that appeal to the imagination is of a stream of waves carrying along little packets or bundles of energy called photons. We cannot specify where each photon is located on a wave of light, but it is possible to locate a large number of them on a statistical or average basis. There is a good reason for this. If one tried to locate a photon with any type of measuring equipment we would need to disturb it. Actually one can speak of light either as a stream of waves or of photons, whichever is more convenient.

Although not all solar energy is visible light, it is convenient to think in optical terms, since even infrared and ultraviolet problems are usually handled by optical techniques. According to this viewpoint, there are six different types of interactions between a light beam and material bodies.

1. Absorption. When light falls on a material and its energy is absorbed by the material, the process can be called optical absorption.

2. Reflection. When a light beam falls on a smooth surface, such that a plane wave incident on the surface remains a plane wave, reflected only in one direction, the process is called specular reflection.

3. Scattering. When light falls on a rough surface, it is sent out from that surface in all directions. This process is one form of scattering.

4. Transmission. Many substances allow light to pass through them. We speak of these as transparent materials. The only effect they have is to change the velocity of the light while it is passing through.

5. Refraction. The velocity of light is less in material substances than in free space. Thus, when a light wave enters a material such as glass at an angle such that the incident beam is not perpendicular to the surface, its direction of travel changes because part of the wavefront of each incident wave is slowed down in the glass.

6. Polarization. Some materials or surfaces have the property of absorbing part of a beam of ordinary light so that the remainder is electrically polarized in a particular direction perpendicular to its line of travel. Such light is said to be polarized in a particular direction. In other cases, a plane wave passing through a material can have its plane of polarization rotated.

To utilize the energy which is associated with solar radiation it is necessary to collect it. The interaction of solar radiation with any one of the constituents of any type of collector is so different that a separate treatment of each constituent is necessary. To treat the problem conveniently in mathematical terms a conventional shallow-basin still is contemplated. A conventional shallow-basin consists in general of an insulated flat absorbing surface painted black to increase absorption. This surface may be presented by a sheet of metal or any number of different materials. An inch or so of water is placed on top of the absorbing surface. Below the absorbing surface some form of insulation is used, such as glass wool, mineral wool, aluminum foil, wood, or dead-air spaces. As a solar still roof, above the absorbing surface are one or more layers of material substantially transparent to solar radiation. Glass has been used exclusively in the past, but certain plastics may work satisfactorily.

To calculate a heat balance for the still, the losses must be established. This could be done by tracing the solar radiation as it strikes the transparent material. Solar energy must first penetrate the transparent material, then the confined atmosphere between the water surface and cover, hence the water layer, and finally be absorbed into the absorbing surface. After the energy has been absorbed it will be re-radiated in the form of thermal energy which will heat up the water layer and accelerate evaporation. Associated with this useful phenomenon are scattering, reflection, and absorption of light energy by different still materials. Some of these losses are inevitable.

Frequently glass is employed as the transparent material. The important properties of glass to be considered are: 1) the index of refraction and 2) the absorptivity of the glass for radiation from sources at different temperatures. Of secondary importance are 3) specific heat, 4) specific weight, and 5) thermal conductivity. The first two characteristics are a function of the wavelength of the incident radiation. One wavelength range to be considered lies between $0.29\mu$ and about $2.5\mu$ and includes the solar and sky spectra. A second range consists only of the invisible, longer wavelength infrared radiation between $4\mu$ and $10\mu$. This range is characteristic of radiating bodies having low temperature. Ordinarily, glass transmits the shorter wavelengths with relative ease, whereas it is entirely opaque to the longer wavelength range. Only the effect of the former need be considered, with glass roofs, therefore, with respect to absorption and index of refraction. It is shown by Parmelee (77) that for all practical purposes both of these properties can be considered to remain constant throughout the wavelength range of the solar spectrum.

Fig. 10 represents the first, second, and several successive internal reflections of a direct radiation striking the surface of a single sheet of glass at the angle of incidence, $i_o$, the intensity of radiation, is designated by $I_o$. This representation assumes no absorption by glass. However, as radiation passes through the sheet of glass a part of the energy becomes absorbed. The schematic, instantaneous heat balance relation for a single glass surface is shown in Fig. 11.

For direct radiation the following formulas which express the transmitted, absorbed, and reflected energy as fractions of the incident energy, were developed by the American Society of Heating and Ventilation Engineers (77).

$$L_1 = \frac{(1 - r)^2}{1 - r^2g^2} \tag{4}$$

$$A_1 = 1 - r - \frac{(1 - r)^2 g}{1 - rg} \tag{5}$$

$$R_1 = r + \frac{rg^2(1 - r)^2}{1 - r^2g^2} \tag{6}$$

Evaluation of these components of radiant energy in the case of sky radiation becomes more involved. To facilitate the analysis, the following assumptions must be made: 1) that the radiation is uniform from all quarters of the sky and is independent of the position of the

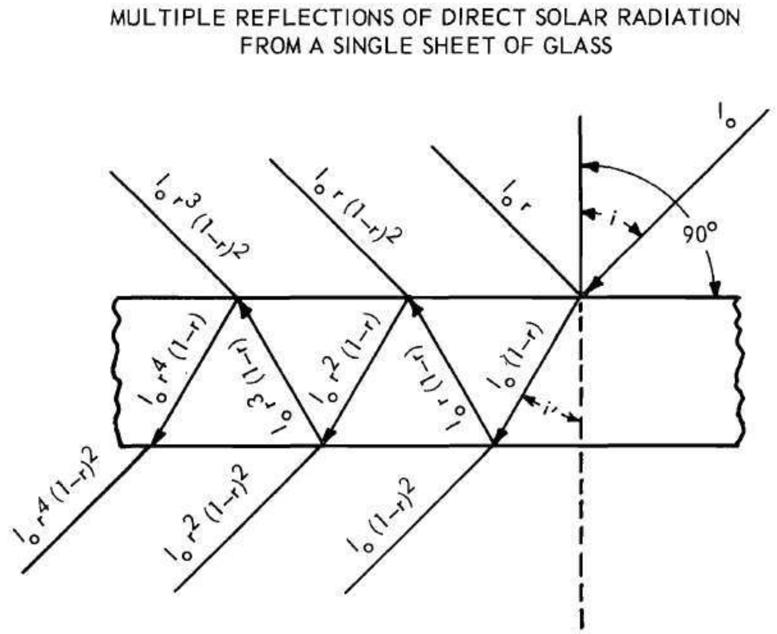


Figure 10.
**Multiple Reflections of Direct Solar Radiation from a Single Sheet of Glass**

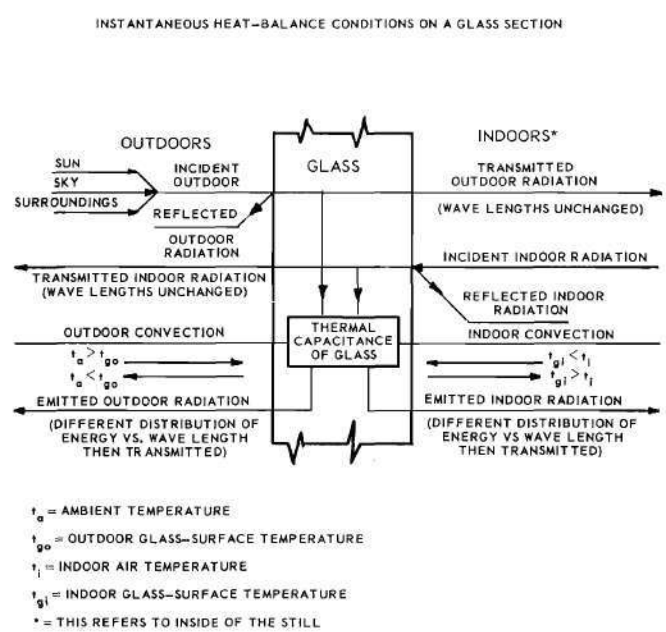


Figure 11.
**Instantaneous Heat-Balance Conditions on a Glass Section**

sun and 2) that the polarization of the sky radiation is negligibly small. On the basis of the above mentioned assumptions and realization that the sky radiation comes from all angles, a graphical integration method was developed by Parmelee (77) to compute the fractions transmitted, absorbed and reflected.

Table 4, which is the result of ASHVE (78, 79) investigation indicates how the transmittance of direct and sky radiation for different glasses are varied.

Table 4. Transmittance Coefficients of Different Glasses

| | Transmittance | |
|---|---|---|
| Sample No. | Normally incident radiation | Sky radiation |
| 1)1/4-inch thickness polished plate glass | 0.71-0.78 | 0.64-0.70 |
| 2)1/4-inch thickness polished plate glass | 0.90-0.91 | 0.81-0.83 |
| 3).29-inch thickness rolled wire heat-absorbing glass | 0.19-0.21 | 0.19-0.26 |
| 6)1/4-inch heat-absorbing polished glass | 0.37-0.42 | 0.37-0.43 |
| 9)double-strength window glass | 0.92-0.95* | 0.81-0.83 |
| 10)heat-absorbing glass | 0.33-0.37 | 0.34-0.46 |

The foregoing discussion is also applicable to sheets of plastic films. The transmissivities of some plastic films were determined by Bjorksten Laboratories (71) and found to be, according to Table 5:

*From Reference (71).

Table 5. Transmittance Coefficient of Different Plastic Films

| | |
|---|---|
| 6-mil translucent polyvinyl chloride | 0.80 |
| 6-mil cast glossy polyvinyl chloride | 0.93 |
| 12-mil clear, glossy polyvinyl chloride | 0.91 |
| 5-mil polyethylene | 0.91 |
| 5-mil clear polyester | 0.88 |

After radiation is transmitted through the transparent material, it also must pass through the condensate. When the transparent solar roof is clean glass or treated plastic, the condensate forms a continuous, thin sheet of water which runs down its side smoothly and therefore, the coefficient of transmissivity through it is very high. However, in the case of untreated plastic material, the condensate is in the form of droplets and the fraction which reflects back is large, causing a great amount of incident energy to be lost.

The residual radiation must pass through the confined space of the still which contains air and water vapor. In this region the radiant energy will undergo some depletion, in the same manner as was discussed in Chapter II, concerning depletion in the atmosphere. However, this loss is not important since the traveling distance for the beam of radiation is extremely short.

In the layer of water, on top of the absorbing surface, the phenomenon is the same as the one already explained in the part on transparent material. The coefficient of reflection, absorption, and transmission is different than that of glass. Since both transmitted and absorbed radiation will be converted into useful heat the only loss from the water layer will be reflection.

After the remaining transmitted radiant energy passes through the layer of water it encounters the absorbing surface. A surface that is exposed to radiation will absorb energy in accordance with the following relationship:

$$H_o/A = \int_0^{\infty} \epsilon_w G_w dw \tag{7}$$

The expression for the total absorptivity, in terms of the total irradiation, is given (80) by the equation:

$$\epsilon = \frac{\int_0^{\infty} \epsilon_w G_w dw}{\int_0^{\infty} G_w dw} = \frac{1}{G} \int_0^{\infty} \epsilon_w G_w dw \tag{8}$$

From an examination of Equation (8), one can readily see that the magnitude of the absorptivity is dependent upon the spectral absorptivity of the absorber and upon the spectral characteristics of the irradiation source, in this case, the sun. The absorbing surface may be built from solid insulators or solid conductors.

When a beam of light energy enters a material, the bound electrons and atoms or ions normally vibrate about their fixed positions in response to the electric and magnetic field of radiation. When the frequency of the existing field is different than the natural frequencies of these electrons or ions, the electrons and ions behave as simple harmonic or sinusoidal oscillators which do not absorb appreciable energy. However, as the frequency of the light energy approaches the natural frequency of the electrons and atoms or ions, resonance of the particles occur, in that they sharply increase the amplitudes of their motions until limited by damping or frictional forces the atom or ion is placed in an excited state. Natural frequencies and damping coefficients for these motions can only be calculated by quantum-mechanics theory, and an intuitive picture of the actual process of energy conversion to heat is highly complex. However, it may be visualized that the electrons and ions can vibrate in various definite energy states, and can lose energy by transfer to a lower energy state, heat, through interactions with other particles in the material, equivalent to collisions in other energy-loss processes.* Solid insulators may be poor absorbers of light energy except at certain narrow frequency bands.

Some of the heat which is evolved through interaction of radiation and molecules of absorbent surface will be conducted through the bottom of the still to the outside and will be lost. A great portion of re-radiated energy will be absorbed in the water layer since the absorption by water in the infrared regions of wave length is large. The remaining reflected energy will be absorbed by water vapor in the enclosed space. This represents a loss.

Considering the hitherto discussed processes, it is now possible to calculate a heat balance for the still. Several investigators, including G. O. A. Löf (81), have studied the heat balance for a simple solar still. To express the heat transfer processes involved several simplifying assumptions are necessary. The principal working assumptions made by Löf are as follows: 1) one-half the sea water charged is evaporated and recovered; 2) heat exchangers are used to preheat sea water to the

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*It must be mentioned that the phenomenon of absorbing radiant energy and degrading it to thermal energy occurs in all parts of the still as already discussed. However, the portion which is absorbed is negligible.

temperature of the cover glass (condensate temperature); 3) miscellaneous heat loss through leakage, edges, etc. is 50 BTU/sq ft/day; 4) distiller absorbs 95 per cent of radiation transmitted through cover; 5) condensate leaves distiller at cover glass temperatures; 6) air circulating in distiller is alternately heated and cooled between basin temperature and cover glass temperature; and 7) distillation rate is substantially uniform over 24 hour period.

On the basis of the foregoing assumptions, the principal equations used by Löf in the heat transfer of the solar still calculations are:

$$H_{sh} = 24Q_g + Q_{bx} \text{ (overall heat transfer rate)} \tag{9}$$

which may be expanded to:

$$H_{sh} = 24(h_{1,c} + h_{1,r})(t_g - t_a)A + \frac{S}{2}(t_b - t_g) \tag{10}$$

and,

$$H_{sh} = 24A\left\{3.19(t_g - t_a) + 0.162\left[\left(\frac{T_g}{100}\right)^4 - \left(\frac{T_a}{100}\right)^4\right] + \frac{0.256(t_b - t_g)^{2.25}}{\frac{W_{da}}{W_{H_2O}}\left(H_{a_b} - H_{a_g}\right)}\right\} \tag{11}$$

and

$$24Q_g = 24Q_{b-a} \text{ (heat balance around cover glass)} \tag{12}$$

which may be expanded to:

$$24A(h_{1,c} + h_{1,r})(t_g - t_a) = 24\left[A(h_{1,co} + h_{r,i})(t_b - t_g) + E\lambda'A\right] =$$

$$= 24A\left\{3.19(t_g - t_a) + 0.162\left[\left(\frac{t_g}{100}\right)^4 - \left(\frac{t_a}{100}\right)^4\right]\right\} =$$

$$= 24A\left\{0.256(t_b - t_g)^{1.25} + 0.156\left[\left(\frac{t_b}{100}\right)^4 - \left(\frac{t_g}{100}\right)^4\right] + \frac{0.256(t_b - t_g)^{1.25}\lambda'}{\frac{W_{da}}{W_{H_2O}}(H_{a_b} - H_{a_g})}\right\} \tag{13}$$

and, $\dfrac{S}{2} = 24\ AE_v$ (evaporation or distillation rate) (14)

which is expanded to:

$$\frac{S}{2} = 24A(h_{1,co})(t_b - t_g)\Big/\frac{W_{da}}{W_{H_2O}}(H_{a_b} - H_{a_g}) \tag{15}$$

$$\text{or,} \quad \frac{S}{2} = 24A\ \frac{0.256(t_b - t_g)^{1.25}}{\frac{W_{da}}{W_{H_2O}}(H_{a_b} - H_{a_g})} \tag{16}$$

The above equations may be used in determining the average operating conditions and the average amount of water produced per day by method of trial and error, the final values satisfying all equations.

Inefficiency of conventional design.--*Considering equation (16) the* amount of condensate is proportional to the 1.25 power of difference between water and glass temperature. Water temperature is directly proportional to solar radiation, but glass temperature is a function of both solar and ambient temperature. This conclusion appears to affect summer production adversely when the ambient temperature is high and maximum water demand exists. Another important feature working against the best operation of the conventional design is that glass temperature is a function of wind velocity. When there is no wind, the production will be reduced substantially.

The inefficiency of the conventional solar still will be further appreciated upon a closer examination of the processes of evaporation and condensation which take place in a single unit. Water will evaporate at any temperature. However, if the water is in a closed tank the space above the liquid surface will soon contain so many free water molecules that their rate of accidental return to the liquid due to their random heat motions will become equal to the rate of escape of new water molecules leaving the surface. When this equilibrium is reached there will be no further change in the relative amounts of liquid and vapor in the tank, and evaporation will cease.

To maintain a positive, forward-going evaporation, it is necessary to remove the vapor as fast as it has been formed. Addition of heat, indeed, is necessary to continue the process. In the conventional solar still, the removal of condensate depends on 1) air movement inside the still (natural convection), and 2) cooling effect of the air outside it. Since one molecule of water can be evaporated only if one molecule be condensed (assuming a certain temperature), if the cooling is not rapid (as in summer), the net effect of increased solar radiation will be raising the temperature of both water and glass. This will result in additional water to evaporate to saturate air space at the higher temperature but not increasing the production. In other words, there is a ceiling value on the production from the conventional solar still, which depends both on the amount of solar energy and the cooling ability of the atmosphere.

Another inherent limitation of the conventional still is the design itself. By combining the three basic and separate processes of energy collection, evaporation, and condensation in one unit, the solar energy depletes considerably through a layer of condensate before reaching the absorbing surface. This constitutes an even greater loss when the condensate is in the form of droplets.

# CHAPTER IV

## EXPERIMENTAL PROCEDURE

Improved solar still and design.--Considering the discussion in Chapter III, one is able to apply several modifications to the conventional design to improve its efficiency. To do so, it was logical to investigate the following:

1) To separate mechanically evaporation from condensation. In such a design the collector-evaporator system will be preserved as one unit while condensation occurs in a separate unit. Mechanical separation of these processes permits the most efficient collection of solar radiation, and at the same time providing a better opportunity for condensation; 2) to increase the rate of evaporation, which is a surface phenomenon, utilization of droplet evaporation may substitute for flat surface evaporation; 3) to remove vapor from the evaporator area, to produce increased evaporation, forced convection replaces natural convection; 4) condenser unit would be utilized advantageously to recover a portion of heat energy; 5) absence of condensate beneath the transparent material because of forced convection, would permit employment of an untreated plastic sheet. After combining the above mentioned changes into a single system, a solar still of the design as shown in Figure 15 resulted and for which the phrase "improved solar still" was coined.

The improved design uses air as an intermediate substance which by both mechanical and physical action will speed up the thermodynamic interchanges necessary for rapid and economic solar distillation.

The air, usually at a higher temperature than sea water (especially in those regions where the water is most critically needed), will come into intimate contact within the still with a shower of spray of preheated sea water. In an external heat exchanger the saturated air will preheat the incoming sea water which simultaneously will cause the vapor to condense as fresh water.

To recover the water content of the saturated air which is at the still temperature, thermodynamic considerations dictate the passage of nearly twenty times the condensate volume of cold sea water through the heat exchanger, attended by a temperature rise of the sea water. This large volume of sea water, at a relatively high temperature, will be stored in the still and in this way provide for the continuous production of fresh water. Whereas droplet evaporation provides for the daytime production, during the remaining portion of the twenty-four hour day, conversion will be based on the deep-basin principle.

Theory.--The evaporation of droplets is a simultaneous heat and mass-transfer operation. The most important and distinctive feature of evaporation from drops is the magnitude of the evaporation rate. Furthermore, if one contrasts the evaporation rate from bulk mass of liquid with the rate for an equal mass of liquid after it has undergone dispersion to drops, it is found that heat and mass-transfer rates increase many fold over the rate for the original bulk of liquid (82). This increase in evaporation rate is due to the tremendous increase in surface area produced by droplet formation, and varies inversely with the diameter of the drop, while the coefficients of the transfer processes also increase inversely with drop diameter.

Evaporation from a droplet usually consists of evaporation from the surface which remains approximately at some constant temperature. The rate can be expressed by heat or mass-transfer relationship introduced by Marshall (82) as follows:

$$\frac{dw}{dt} = \frac{h_c A_h (\Delta t)_m}{\lambda_s} \tag{17}$$

or:

$$\frac{dw}{dt} = K_g A_m (\Delta P)_m \tag{18}$$

Experimental studies have established empirical correlation for $h_c$ and $K_g$. Representative of these are the following semi-empirical equations proposed by Ranz and Marshall (83, 84), which are useful for estimating heat and mass-transfer coefficients.

$$\frac{h_c d}{K_f} = 2.0 + 0.60\left(\frac{v_a d \rho_a}{\pi}\right)^{1/2}\left(\frac{C_p \omega}{K_f}\right)^{1/3} \tag{19}$$

or:

$$\frac{K_g d P_f}{D_v P_a} = 2.0 + 0.60\left(\frac{v_a d \rho_a}{\pi}\right)^{1/2}\left(\frac{D_v \rho_a}{\pi}\right)^{1/3} \tag{20}$$

Each term in parentheses is dimensionless. For zero velocity, $v_a = 0$. Equations (19) and (20) reduce to the theoretical expression for $h_c$ and $K_g$ as follows:

$$(h_c)_o = 2K_f/d \tag{21}$$

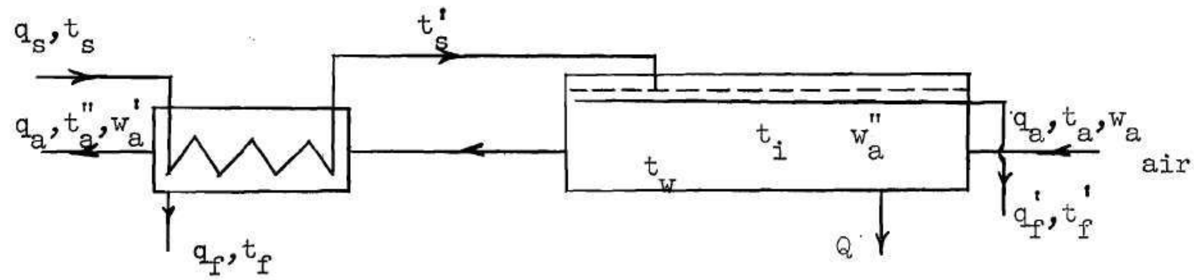
$$(K_g)_o = \frac{2D_v \rho_a}{d P_f} \tag{22}$$

Equations (19) to (22) show that the magnitude of the coefficients $h_c$ and $K_g$ increase inversely with the drop diameter d, other conditions remaining constant. However, since Reynolds number $\frac{v_a d \rho_a}{\pi}$ decreases when d decreases, only equations (21) and (22) predict the inverse relationship at all times.

The rate of vaporization of liquids into turbulent gas streams has been the subject of considerable study because of a wide interest in the many practical applications of the quantitative result. Transfer across the turbulent gas stream is mainly by eddy diffusion, which is quite rapid, compared with molecular diffusion.

Extensive studies of Maisel and Sherwood (85) definitely indicate that the value of mass-transfer coefficient increases as turbulence increases. A higher Reynold's number results in more transfer of mass.

To acquire knowledge of the performance and production of this new design, a complete heat balance calculation of the process is necessary. Considering sketch below, it is possible to isolate a unit of




collector-evaporator and condenser from environment and study the system in terms of the input and output of energies according to the Law of Conservation of Energy or Mass.

Energy balance could be written as:

$$H_a = 3.69H - \frac{H_1 + H'_1 + H''_1}{A} \tag{23}$$

where 3.69 is the conversion factor for converting gram-cal/$cm^2$/day to BTU/sq ft/day. Formula (23) could be further extended by considering the value of losses. The value of loss is composed actually of three parts: 1) convection loss from the exposed surface, 2) radiation loss, and 3) conduction loss through insulation at the bottom of the tank.

Estimation of each component is possible through a heat transfer expression. Cooling effect of wind in the case of a cylindrical mass, as at the top of the solar collector, could be calculated from the heat transfer formula given by King and Knaus (86), as follows:

$$H_{l,c} = (0.25)24V^{0.58}\left(\frac{1 + 0.000576\ t_a}{D^{0.42}}\right)(t_i - t_a) \qquad (24)$$

Telkes (87) expresses the loss due to radiation with the following equation:

$$H_{l,r} = \frac{(t_p + 460)^4 - (t_a + 460)^4}{t_p - t_a}\,\sigma \qquad (25)$$

Heat loss due to conduction from the bottom of the still through insulation is:

$$H_{l,co} = \frac{K(t'_w - t_a)}{d} \qquad (26)$$

$H'_l$ is a function of temperature, geometry, and material of condenser which must be evaluated in any special case, but generally the equations (24) to (26) are applicable. $H''_l$ is relatively small and could be neglected. However, its calculation is possible through equations (24) to (26).

Combining equations (23) to (26) will yield:

$$H_a = 3.69H - \left\{\left[(0.025)\,\beta\,(24)\,V^{0.58}\left(\frac{1 + 0.000576\,t_a}{D^{0.42}}\right)(t_i - t_a) + \right.\right.$$

$$\left.\left. + \sigma\beta\,\frac{(t_p + 460)^4 - (t_a + 460)^4}{A(t_p - t_a)} + \frac{K(t'_w - t_a)}{Ad\,\beta_1}\right] - \frac{H'}{A}\right\} \qquad (27)$$

Another way to calculate the value of $H_a$ is through a heat balance equation for the entire system as follows:

$$H_a = (q_a w_a - Cq_a)(t''_a - t_a) + (q_a w'_a - q_a w_a)\lambda + q_f(t_f - t_s) +$$

$$+ q'_f(t'_f - t_s) + Q'(t''_w - t_s) \qquad (28)$$

because

$$E = \frac{H_a}{3.69H} \qquad (29)$$

and since the following equations are correct:

$$q_f = (1 - \alpha)Q - q_a\,(w''_a - w'_a) \qquad (30)$$

or:

$$q_a = \frac{(1 - \alpha)Q}{w''_a - w'_a} \qquad (31)$$

and:

$$Q' = q_s - Q - (q_a w'_a - q_a w_a) \qquad (32)$$

and:

$$q_s(t'_s - t_s) = \lambda\,(1 - \alpha)Q + (cq_a + W'_a q_a)(t_i - t''_a) \qquad (33)$$

or:

$$q_s = \frac{\lambda(1 - \alpha)Q + (cq_a + w'_a q_a)(t_i - t''_a)}{t'_s - t_s} \qquad (34)$$

Inserting values of $Q'$ and $q_a$ as $Q$ in equation (28) we have:

$$H_a = \frac{(1-\alpha)Q}{w''_a - w'_a}(w_a + c)(t''_a - t_a) + \frac{(1-\alpha)Q}{w''_a - w'_a}(w'_a - w_a)\lambda + q_f(t_f - t_s) +$$

$$+ (1-\alpha)Q(t'_f - t_s) + \left[\frac{\lambda(1-\alpha)Q + c\frac{(1-\alpha)}{w''_a - w'_a}Q + w'_a(t_i - t''_a)}{(t'_s - t_s)} -\right.$$

$$\left. - \; Q - \frac{(1-\alpha)Q}{w''_a - w'_a}(w'_a - w_a)\right](t''_w - t_s). \qquad (35)$$

Equations (27) and (35) together determine the operation of the system. However, any direct practical application is extremely cumbersome unless some simplification is achieved. This may be accomplished by assuming: $t_s = t''_a = t_f$; $t'_s = t_i = t_w$; $t_p = \frac{t_i + t_a}{2}$; $t''_w = t_a = t'_f$; which actually does not introduce any significant error.

Then for any value of $t_i$ equation (27) can be solved and $H_a$ can be estimated. Knowing $H_a$, from equations (29) E could be calculated, since H is a measurable value. Equation (35) may be simplified to:

$$3.69\ H = \frac{1-\alpha}{w''_a - w'_a} Q\lambda(w'_a - w_a) - \alpha Q(t_a - t_s) + \lambda(1-\alpha)Q\frac{t_a - t_s}{t_i - t_s} \qquad (36)$$

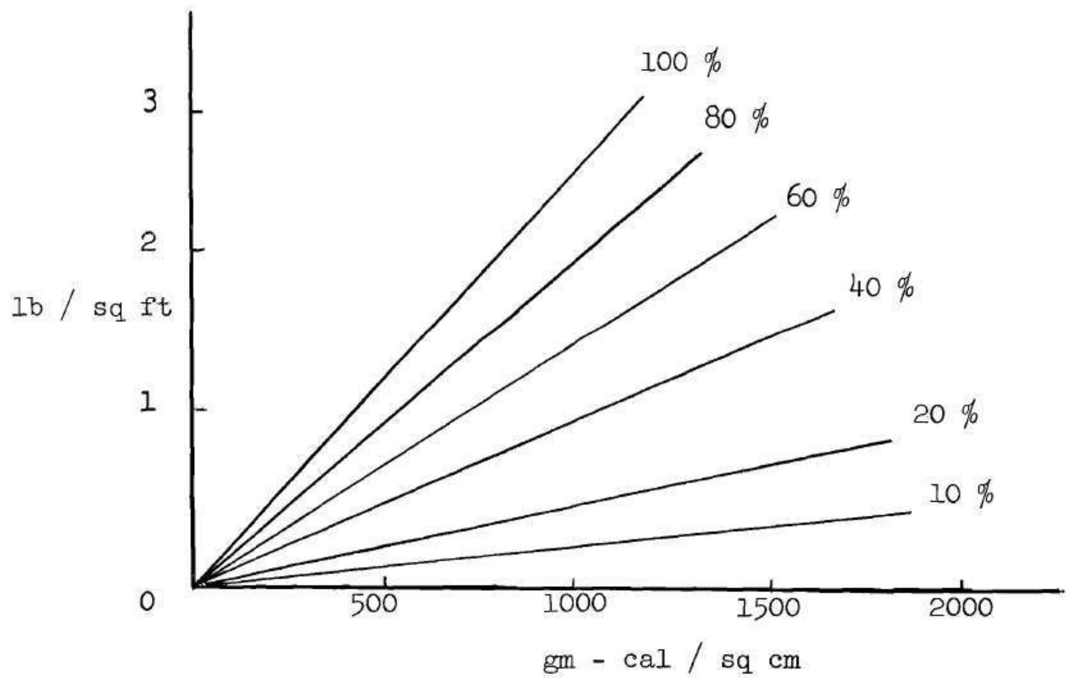
or:

$$Q = \frac{3.69\ EH}{\lambda(1-\alpha)\left(\frac{w'_a - w_a}{w''_a - w'_a} + \frac{t_a - t_s}{t_i - t_s}\right) - \alpha(t_a - t_s)} \qquad (37)$$

Equation (37) is consistent with the condition that with zero solar energy there will be no production.

In this equation $w_a$, H, $t_a$, $t_s$ are fixed values, and are known. $\alpha$ has a value between 0.1 and 0.2 while $W'_a$ and $W''_a$ are a function of $t_s$ and $t_i$ and readily can be found from a psychrometric chart. $\lambda$ also varies with $t_s$ and its value is known for any temperature.

A graphical solution for equation (37) facilitates calculations. For any temperature, $t_i$, the value of Q can be plotted versus the solar energy. Since for any value of E there will be a curve which passes through origin a family of curves will need to be produced. A graph for $t_i = 90°F$ is shown in the following graph. For plotting this graph it is assumed that $t_s = 75°$ and $t_a = 83°F$.




Experimental setup and instrumentation.--The experimental plant was located on top of the Chemistry Annex Building, Campus of Georgia Institute of Technology in Atlanta; latitude 33°, 46', 45" North.

Five different designs were built and tested. In addition four different operational schemes of Still IV were studied. Figures (6), (8), (12), (13), (14), show the experimental setup. Details of each design are shown in Figures (7), (9), (15), and (16). Each still has a horizontal surface area of 9 sq ft, 16.5 inches wide, and 78.5 inches long, All stills have plastic covers of transparent material (Mylar, type W) except Still V which is covered by 3/16 inch thick window glass. The transparent roofs make a slope of 45° with the horizontal, except variation no. 2 of Still IV which had a 30° slope.

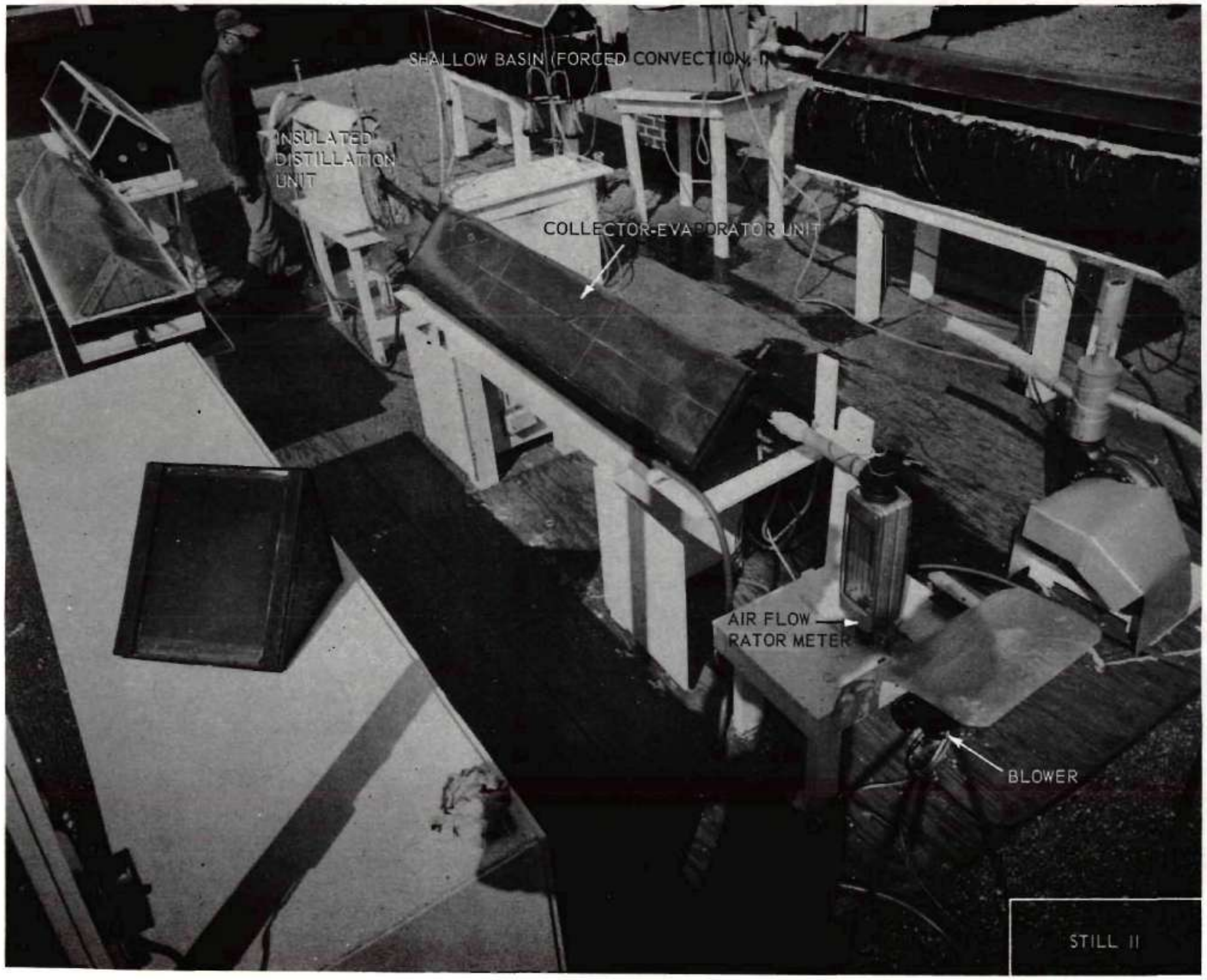
The principal features for each of these stills are briefly:

1) Deep Basin Still I. This still represents an insulated deep-basin design, permitting accumulation of a water depth up to 13 inches inside the still. (Figure 9)

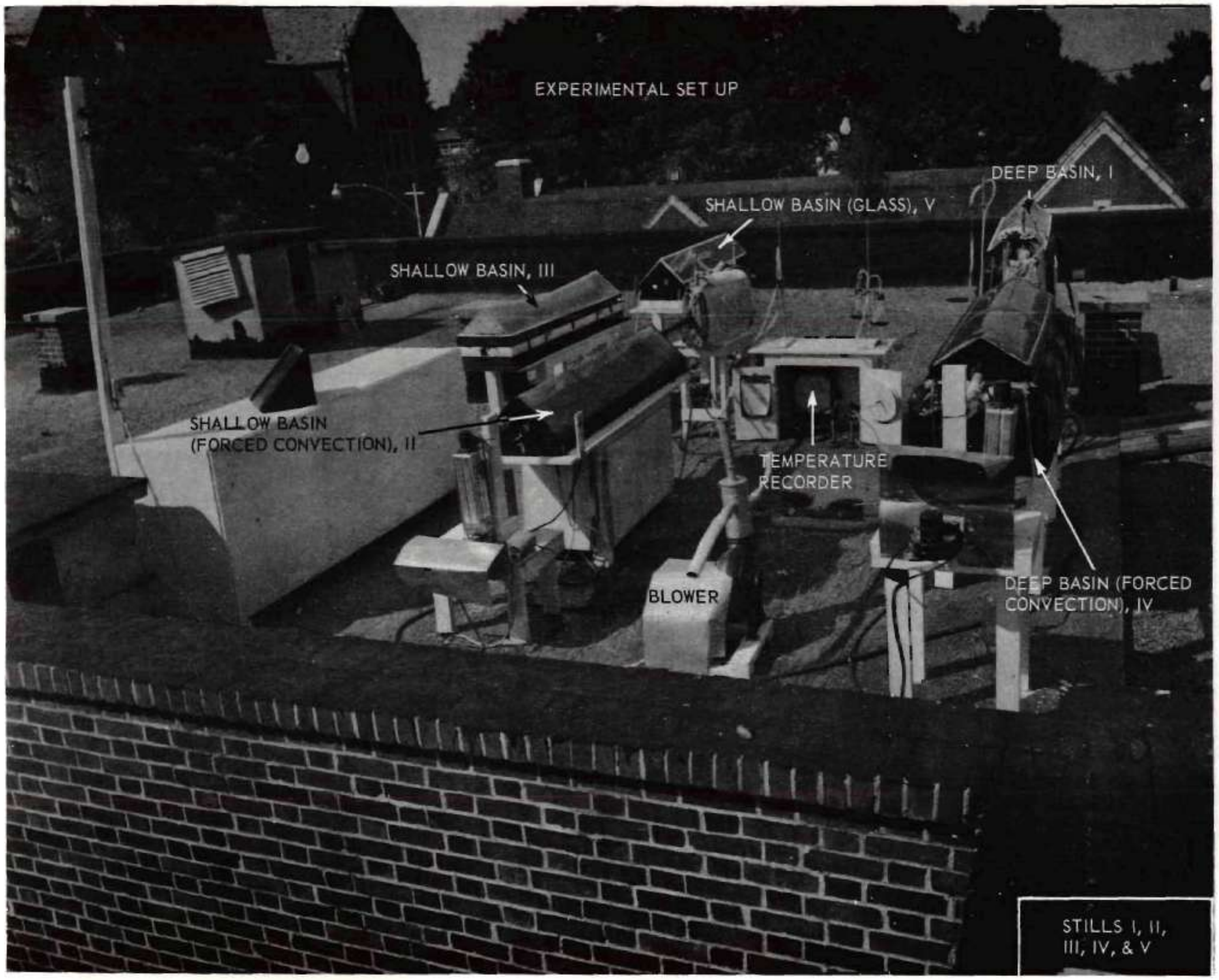
2) Shallow Basin (Forced Convection), Still II. In this still the collector-evaporator unit has been completely separated from the condenser. A continuous flow of air is maintained through the collector during the day, above the one-inch layer of water. The forced air is cooled to the incoming raw water temperature in the condenser. Balance between hot saturated air inside collector and cool saturated air at raw water temperatures is collected as fresh water. The effluent form the condenser is wasted to drain. (Figures 12 and 16)

3) Shallow Basin Still III. It is a shallow basin design with 1 1/2 inches of water inside. (Figure 7)

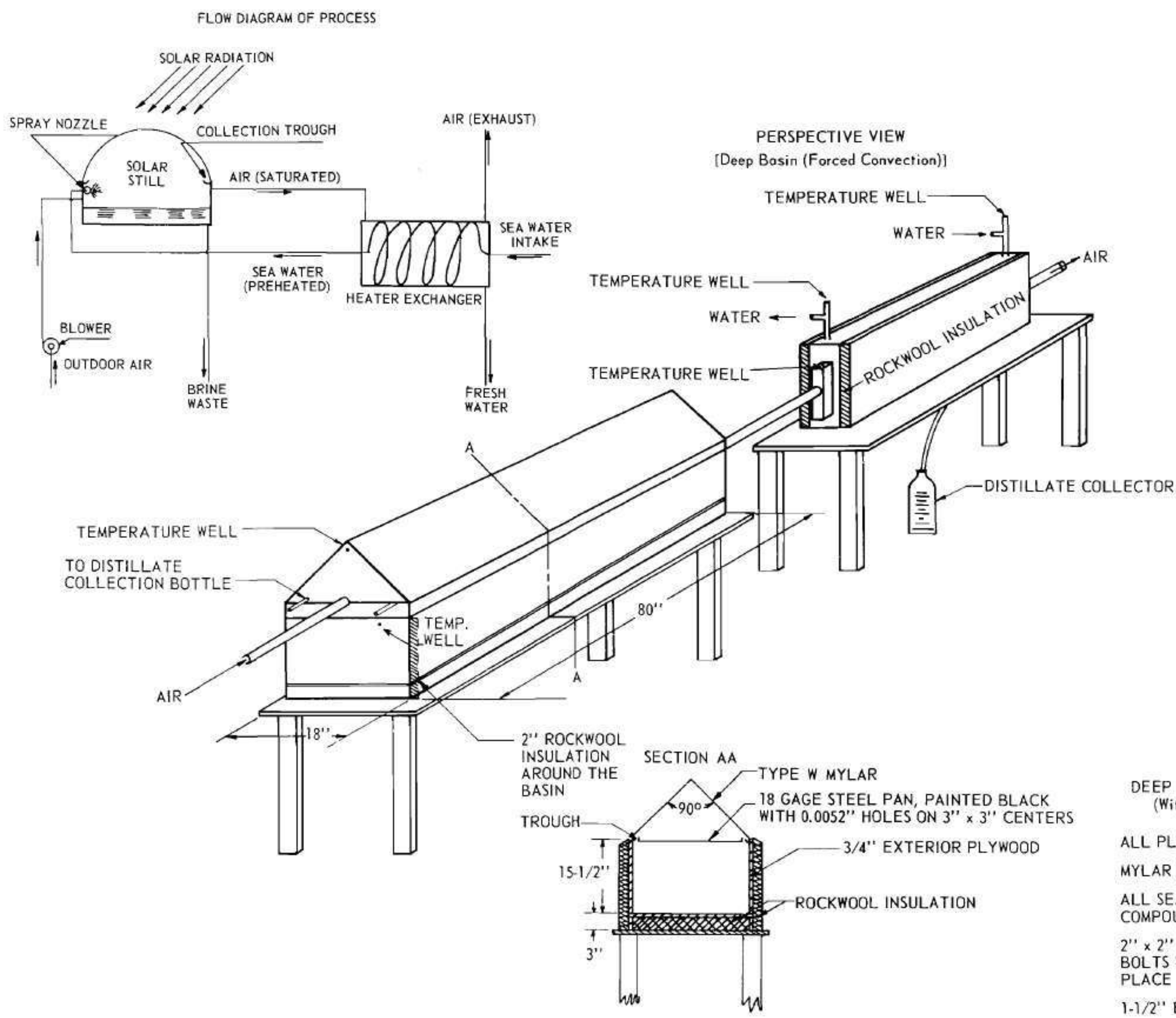
4) Deep Basin (Forced Convection), Still IV. It is a combination of Still I and Still II, e.g., the collector evaporator unit being a deep basin design is separated from the condenser. During the day air is blowing through the still and fresh water is collected in the



SHALLOW BASIN (FORCED CONVECTION)
INSULATED DISTILLATION UNIT
COLLECTOR-EVAPORATOR UNIT
AIR FLOW RATOR METER
BLOWER
STILL II


EXPERIMENTAL SET UP
DEEP BASIN, I
SHALLOW BASIN (GLASS), V
SHALLOW BASIN, III
SHALLOW BASIN
(FORCED CONVECTION), II
TEMPERATURE
RECORDER
BLOWER
DEEP BASIN (FORCED
CONVECTION), IV
STILLS I, II,
III, IV, & V


DEEP BASIN (FORCED CONVECTION) IV
MYLAR
INSULATED HEAT EXCHANGER
COLLECTOR - EVAPORATOR UNIT
AIR FLOW RATOR METER
RECIRCULATION PUMP
WATER FLOW RATOR METER
DISTILLATE
STILL IV




STILL IV

DEEP BASIN (FORCED CONVECTION)
(With External Heat Exchanger)

ALL PLYWOOD IS 3/4'' 5-PLY EXTERIOR

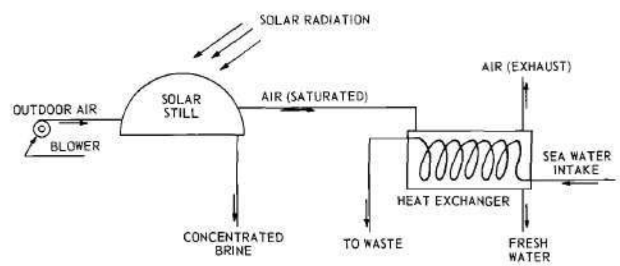
MYLAR PLASTIC IS 0.005'' THICK

ALL SEALING IS DONE WITH CAULKING COMPOUND

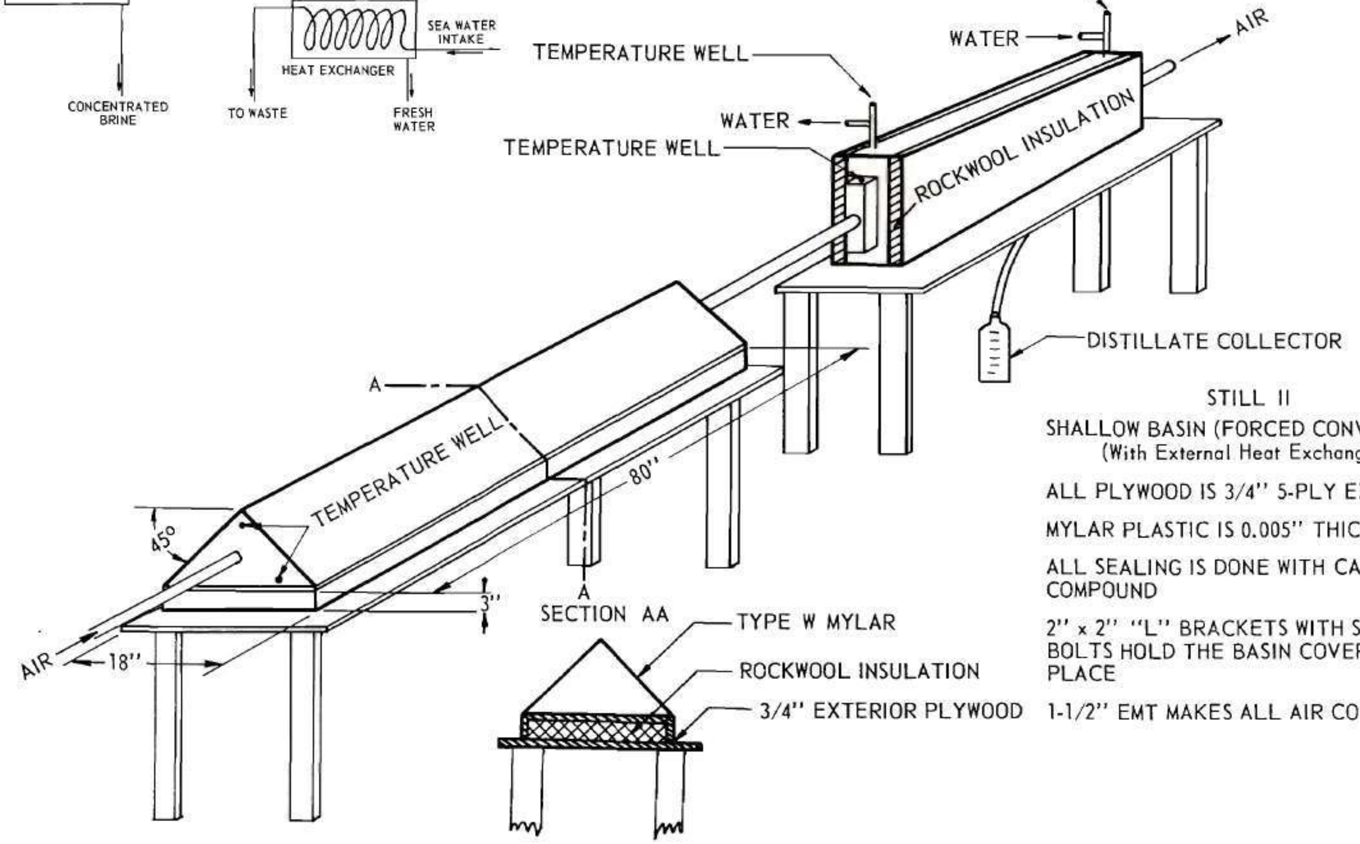
2'' x 2'' ''L'' BRACKETS WITH STOVE BOLTS HOLD THE BASIN COVER IN PLACE

1-1/2'' EMT MAKES ALL AIR CONNECTIONS

FLOW DIAGRAM OF PROCESS




PERSPECTIVE VIEW
[Shallow Basin (Forced Convection)]




STILL II

SHALLOW BASIN (FORCED CONVECTION)
(With External Heat Exchanger)

ALL PLYWOOD IS 3/4" 5-PLY EXTERIOR

MYLAR PLASTIC IS 0.005" THICK

ALL SEALING IS DONE WITH CAULKING COMPOUND

2" x 2" "L" BRACKETS WITH STOVE BOLTS HOLD THE BASIN COVER IN PLACE

1-1/2" EMT MAKES ALL AIR CONNECTIONS.

condenser. Also the top is provided with troughs in order to collect the condensation on the surface of the plastic cover during the night. (Figure 14)

Another variation of this basic design was studied. In the design a perforated, galvanized tray, painted black, was attached near the top of the still. (Figure 15). A small pump was installed to circulate the water from the basin to the top of the tray, which drains back to the bottom of the still, provides a shower of droplets. The slope of the roof is 30° instead of 45°.

5) Shallow Basin (Glass), Still V. It is a conventional design with a glass roof. Except for the cover, it is quite similar to Still III in construction. This unit was primarily constructed to furnish a comparison with the stills described above and therefore acts as the control. (Figures 6 and 7)

All stills are so constructed that the roof may be separated from the bottom, except Still II which is one unit. Troughs for collecting fresh water condensed beneath the cover are installed in all the stills except for II. These troughs are built from 20-gauge galvanized sheet metal and are connected to the top part of the stills. All are painted white, except in Still IV which is painted black. White paint is used to prevent re-evaporation of condensate which is collected in the troughs. Troughs in Still IV do not collect distillate during the day light hours. The troughs are provided with the proper slope to assure gravity transport of the fresh water to the storage tanks.

The main bodies of all the stills were built from 3/4 inch, exterior plywood. At first 4 mils black polyethylene was used as lining for the dual purpose of sealing and providing an absorbing surface. This design functioned poorly as the polyethylene film was easily punctured during construction. In a later design, sealing was achieved by applying white caulking compound. The result was very satisfactory and no difficulties were encountered. Leakage of air through the spaces between the top and bottom part was prevented by using weather stripping. This weather stripping was first covered with a caulking compound and then placed between the two parts of the still. Reasonable pressure was then applied by tightening a system of bolts and nuts, connecting a series of braces that are attached to the top and bottom parts of the still.

The absorbing surface for all the stills was the plywood which was painted black, except for variation no. 2 of Still IV in which a 20-gauge, galvanized sheet, painted black acted as shower spray tray, is used as the absorber.

Weatherable, type W, Mylar, a registered trade mark for a recent DuPont brand of polyester film, five mils thick, was used as the cover in Stills I to IV. Mylar, type W, is a light weight, high-strength, transparent film that initially was developed for greenhouses. As reported by DuPont the transmissivity of type W Mylar is essentially the same as window glass. Their experiment shows (88) that in the higher energy regions of the solar spectrum the transmissivity of type W Mylar is very close to 1/8 inch thick window glass. For the dimensions of our stills there was no need for any kind of structural support for these plastic films.

To blow the air through Still II and IV, two single stage, direct driven, 1/8 hp blower were used. The capacity of these blowers is 30 cfm with .9 inches of static water pressure. Provisions for adjusting the flow rate were included from the beginning.

The condenser used in Still II and IV consists of American Blower Cooling Coils made by the American Blower Corporation. These cooling coils are made of 3/8 inches I.D. seamless copper tubing with .025 inch wall thickness. The tubing is helically wound with 13/32 inch fins in regular spacing. The fin material is copper-coated, with a tin-lead mixture which seals the mechanical connection and gives a permanent metallic bond. It consists of one circuit having 28 rows. Side casings are built from 14-gauge galvanized steel. It was found that insulation of this condenser is very important. When it is exposed to solar energy they heat up and the cooling efficiency is very low. Glass wool, two inches thick, is used as insulation material for the exterior of the condenser.

To study the performance and operation of different stills, the following information was collected.

1. Temperature, at different points;
2. Air flow passing through Stills II and IV;
3. Water flow passing through the condensers of Stills II and IV;
4. Ambient temperature and humidity;
5. Solar energy available at horizontal surface;
6. Fresh water produced.

The temperatures are measured by 12-inch-long Weston Industrial Dial Thermometers. The range of the thermometer is 20 to 240°F and is accurate within one per cent of its range. It utilizes an improved bi-metal, multiple helix which responds quickly to changes in temperature. A two-point liquid-filled system temperature recorder* made it possible to preserve a permanent record of instantaneous changes of temperature at any two points where continuous temperature measurements were desirable.

For measurement of the flow of air one 1700 series Flowrator meter*, is used for each still. The Fischer and Porter Series 1700 Flowrator Meters operate on the variable area principle to meter fluid flow. This meter is comprised essentially of a tapered glass metering tube, float, float stops, end fitting, and side plates. The elevation of the float in the tapered glass metering tube is proportional to the fluid flow rate. The scale is graduated to provide percentage of flow, 100 per cent being equivalent to 10.4 scfm, where the specific gravity of gas is 1.0 at 14.7 psi and 70°F. The flowrater meter exerts head loss of .79 inch of water as the friction loss in the system.

For measuring the amount of water passing through the condensers, two types of flowrater meters are used: 1) 2700 Series of Fischer and Porter, working on the same principle as 1700 Series graduated to 100 per cent with 100 per cent = 4.35 GPM, 2) the Tri-Flat meter measures to 700 cc/min of raw water. This is used to measure the lower ranges of water flow.

The ambient temperature and relative humidity are measured with two Hygrothermographs, Model 160**. The chart of this instrument is

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*Manufactured by Fischer and Porter Company, Hatboro, Pa.

**Manufactured by Friez Instrument Division, Bendix Aviation Corporation.

graduated for temperatures from 0-110°F and for relative humidity 0-100 per cent.

To measure the solar intensity and available energy on the horizontal surface, the Atlanta Weather Bureau measurements were used. The Atlanta Weather Bureau utilizes an Epply Pyrheliometer to measure the total solar energy received in cal/cm$^2$/day. The Epply Pyrheliometer (89) is a specialized thermopile made with wire of an alloy of 60 per cent gold and 40 per cent palladium against wire of an alloy of 90 per cent platinum and 10 per cent rhodium. The wires are 0.0016 inch diameter. Alternate junctions are in thermal contact with concentric silver rings, 0.01 inch thick, but are electrically insulated from them. The receiving surface of the inner ring is black and that of the outer ring is white. The receiving element is hermetically sealed in a lamp bulb of soda lime glass which transmits about 10 per cent of the incident radiation at 2900 A°. At the time of the sealing, the bulb was carefully heated and exhausted to expel absorbed moisture and is then filled with dry air to prevent any condensation of moisture on its inner surface due to exposure to low temperatures. The bulb, which is three inches in diameter, is mounted on a metal base with leveling screws. Heavy copper leads are provided for connection to the indicating or recording apparatus. The approximate overall dimensions of the instrument are: height, 6 1/2 inches; diameter of the base, 7 1/2 inches.

The inner or hot ring is painted with lampblack and the outer or cold ring is smoked with magnesium oxide. These blackened and whitened surfaces absorb longwave radiation equally well, but the magnesium oxide has a high coefficient of reflection for radiation having the wavelength of solar radiation. Therefore, when exposed to solar radiation the two rings of this pyrheliometer develop a marked temperature difference, and the resulting electric current shows an emf which as shown by the Bureau of Standards tests is not strictly proportional to the difference between the temperature of the junctions attached to the black and the white rings respectively. The voltage is very nearly proportional to the intensity of the solar radiation.

This instrument must be calibrated to give the amount of solar energy received by a horizontal surface.

In connection with this Epply Pyrheliometer, a Brown Special Fast Speed Electronik Recorder is used to record the solar intensity. The range is 0-2 gram calories per minute per square centimeter.

Measurement of produced fresh water was achieved with graduated jars, acting as collecting tanks. However, this procedure proved to be very time-consuming and unable to yield the instantaneous rate of production. Therefore, a measuring device was designed and constructed* to facilitate the measurement of production and its rate. The instrument sketch is shown in Figure 17. It consists of an extracting syphon which has the capacity of 28 ml, and automatically empties itself as soon as the water level reaches the level equal to highest point of syphon. Two platinum electrodes are so installed that when water reaches the highest level it makes contact and activates an electrical circuit. The low current will be amplified with an amplifier tube and in turn will activate a plate relay. This plate relay will close a solenoid circuit which in turn will move a pen and mark the chart. The number of registered marks indicates the flow rate.

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*This instrument was designed in cooperation with Mr. Roy Peek and Mr. Jimmy G. Lee and constructed by Mr. Ross Hughes.

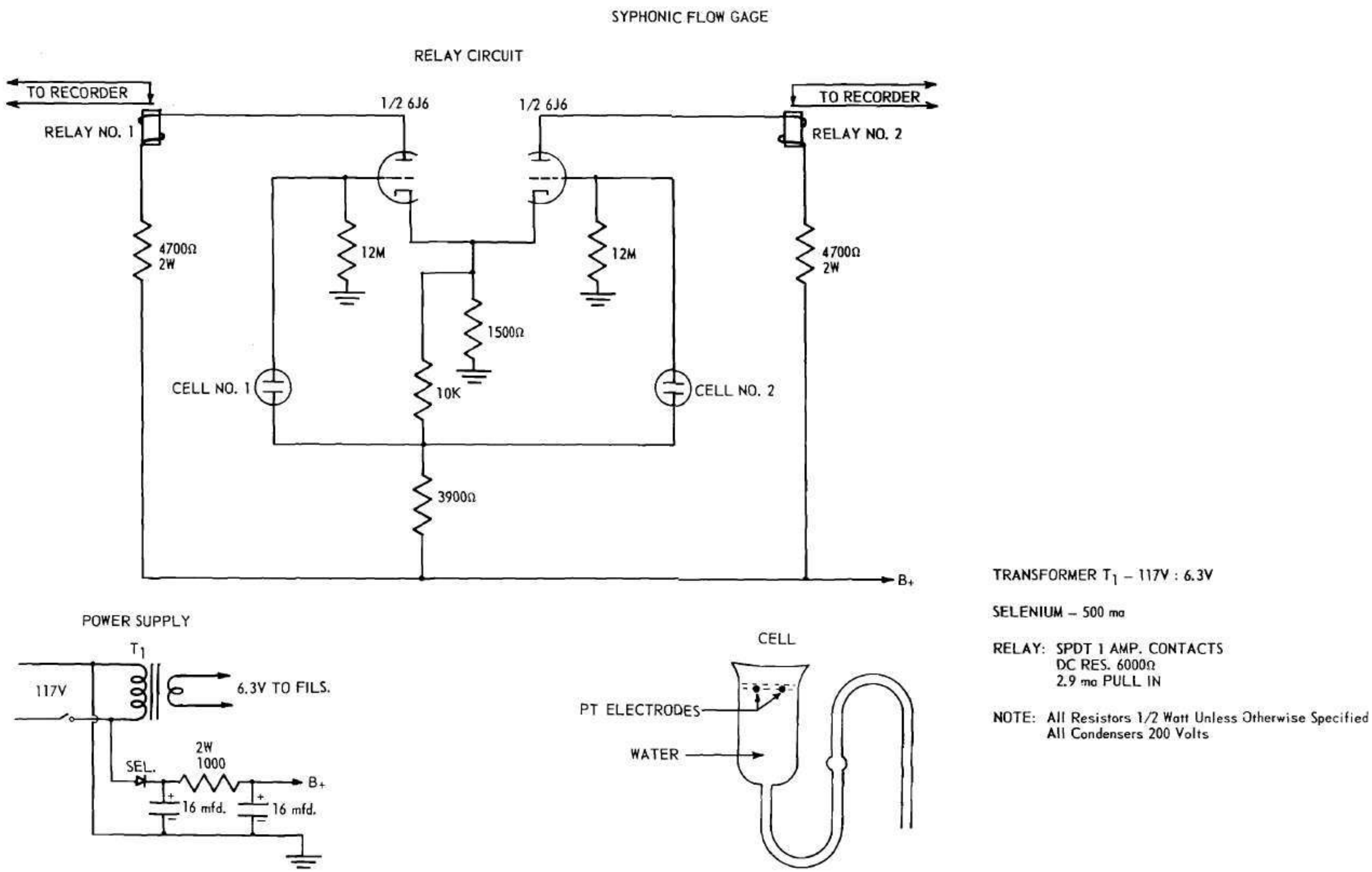



Figure 17.
Syphonic Flow Gage

Since it was necessary in Still II and IV to turn the blowers on and off at sunrise and sunset, respectively, an Intermatic time-clock switch was installed early in the summer of 1959. This expedient also saves many man-hours.

# CHAPTER V

## EXPERIMENTAL DATA AND DISCUSSION OF RESULTS

Collection of data from the operation of each of the different stills was started as soon as construction was complete. A considerable period of time was necessary to test each still against leaks and other constructional defects to insure that each would be operating according to its original design. Reliable data were collected for each still according to the schedule shown below:

Still I : Deep Basin from May 19, 1959 to September 30, 1959.

Still II : Shallow Basin (Forced Convection), May 19, 1959 to September 30, 1959.

Still III: Shallow Basin (Forced Convection), May 19, 1959 to September 30, 1959.

Still IV : Deep Basin (Forced Convection)
- a. Prior to insulation and forced convection from June 11, 1959 to August 15, 1959.
- b. Insulated, but without forced convection from August 15, 1959 to August 25, 1959.
- c. Forced convection and with external heat exchange from August 25, 1959 to September 30, 1959.

Still V : Shallow Basin (Glass), from July 24, 1959 to September 30, 1959.

Data were collected until August 25, 1959 on the average of four times daily, with one of these readings definitely taken early in the morning and the other late in the afternoon. After August 25, 1959 readings have been collected on an hourly basis between 7 or 8 a.m. to 5 p.m., and continued then every other hour until 11 p.m. This intensive program of reading was continued until September 30, 1959.

Readings from 7 or 8 a.m. to 7 p.m. are assumed to constitute the daylight hours' production from solar energy for that day. Data from 7 p.m. to 7 or 8 a.m. the next morning are considered night time production for the same day. Total production is the sum of these two values.

Since in any solar still system there are a number of uncontrollable variables which affect its operation, the known variables were eliminated as far as possible. In order to eliminate the effect due to geometry it was decided to construct and design all experimental stills of equal size. This provision permitted the most direct and reliable comparisons. Another important factor considered to affect the operation is the quantity of water stored in the stills. Therefore, all shallow basins were designed to have the same capacity as were all deep basins. As many as nine gallons of water are maintained within the shallow basin stills during experimentation. Inside the deep basins 44 gallons can be held. Generally, early each morning water was added to maintain the same volume inside the stills. To reproduce the same volume from day to day this was controlled by means of water level indicator shown in Figure 6.

Tap water instead of salt water was used in these experiments. This is permissible and does not affect the theoretical evaluation of processes because thermodynamically speaking the vapor pressure of sea water with a salt content of 30000 PPM is only slightly less than pure water (76). However, operation with sea water presents a number of practical difficulties which in the case of tap water would not be encountered. Haste was required to have the equipment in operation during the summer of 1959.

To compare the operation of the experimental stills with the conventional, shallow basin design, it is desirable initially to study the operational data from each still separately.

Operational characteristics of deep basin.--The production is a function of the difference between the temperature of water and transparent material, which is closely related to ambient temperature. When this temperature difference increases production will increase and when it decreases distillation will be less. Hourly variation of temperature inside the Deep Basin and also ambient temperature, for a typical day is shown in Figure 18. Figure 18 shows that on September 20 until 6 a.m. the difference between ambient temperature of the air (outside) and the water (inside) is considerable. After the sun rises this difference becomes smaller and smaller. About noon this difference reaches its minimum. At 2 p.m. a drpp in ambient temperature is observed, probably due to heavy clouds or possibly a shower. The effect on the water temperature is much less pronounced because water has a higher heat capacity than air. After 2 p.m. the air temperature again rises and so does the water temperature. After 4 p.m. the air temperature declines for the day while the water temperature in the still rises for another one and a half hours, and then drops off but at a much slower rate compared to the air temperature. The slower cooling of the water results from the fact that the basin is insulated and contains a large volume of water. Although the value of the sun's energy declines, the incoming heat still exceeds the losses which are small and slow in the case of the insulated deep basin. The phenomenon is due to the fact that the water temperature is never much higher than the ambient temperature during the period of

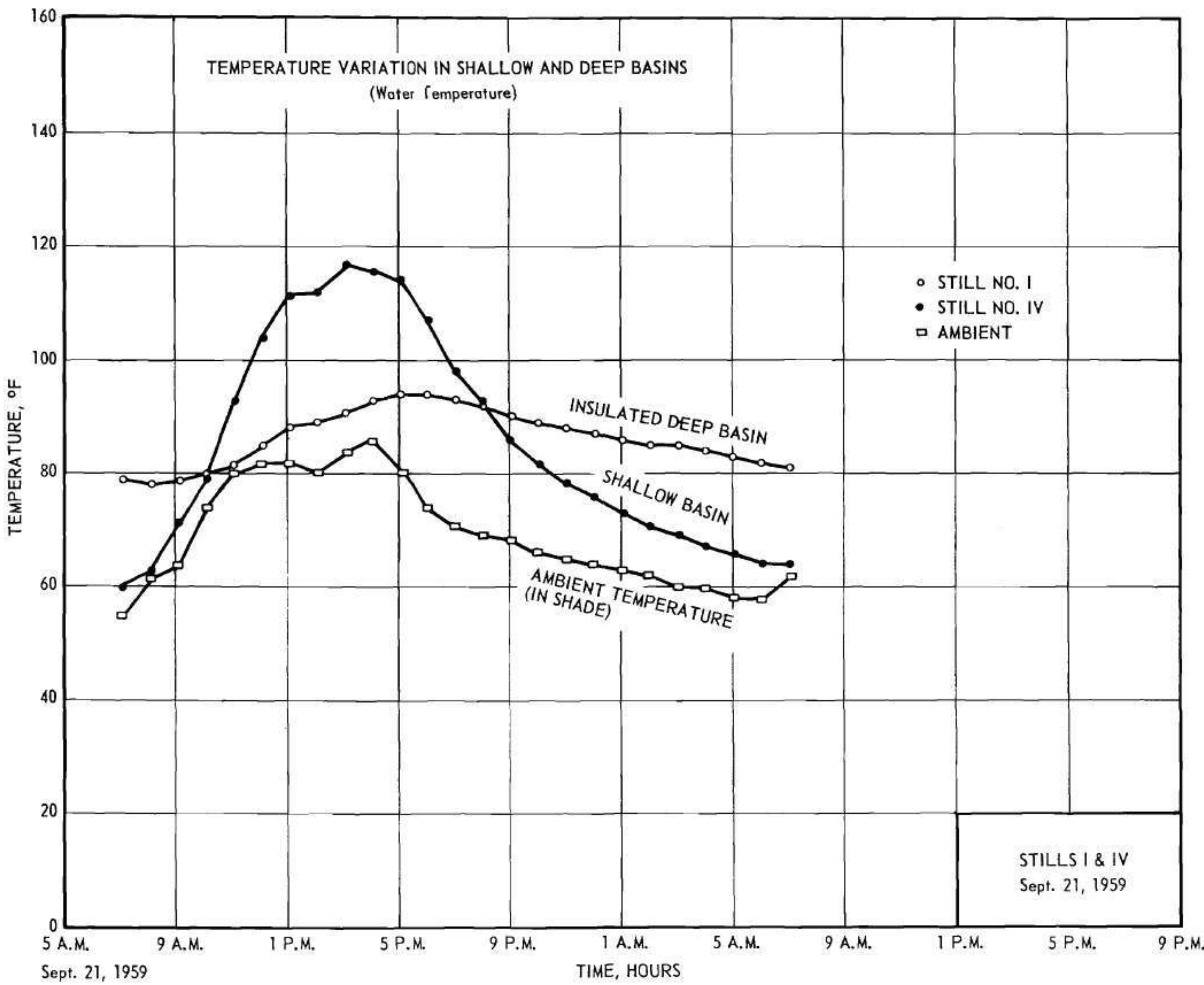



Figure 18.

**Temperature Variation in Shallow and Deep Basins (Water Temperature)**

greatest solar insolation. As the night progresses, the difference between these two temperatures increases further. On the basis of temperature variations one could expect that early in the morning, between 7 a.m. and 9 a.m. water will be produced in faster rate than period between 9 a.m. and 5 p.m. and also night production will be considerably higher than daylight hours. This deduction is correct as can be seen from the following table which shows the hourly production of the water.

Table 6. Hourly Distillate from Deep Basin Still

September 21, 1959

| Hour | 8-9 | 9-10 | 10-11 | 11-12 | 12-1 p.m. |
|---|---|---|---|---|---|
| Distillate (mls) | 100 | 20 | 30 | 40 | 10 |

| Hour | 1 p.m.-2 | 2-3 | 3-4 | 4-5 | 5-7 | 7-9 | 9-11 | 11-8 a.m. |
|---|---|---|---|---|---|---|---|---|
| Distillate (mls) | 0 | 10 | 25 | 15 | 50 | 175 | 250 | 525 |

Figure 19 represents cumulative water production for Deep Basin, Still I on August 27, 1959. The same typical operational behavior may be noted here. On August 27, Still I produced during the daylight hours 470 mls while from 7 p.m. to the next morning about 750 mls or about 160 per cent more than during the daylight hours. The behavior is typical for the Deep Basin Still, producing more during the night than during the daylight hours. Actually production depends on the difference of temperature between water and transparent material, or $t_p - t_w$. During the

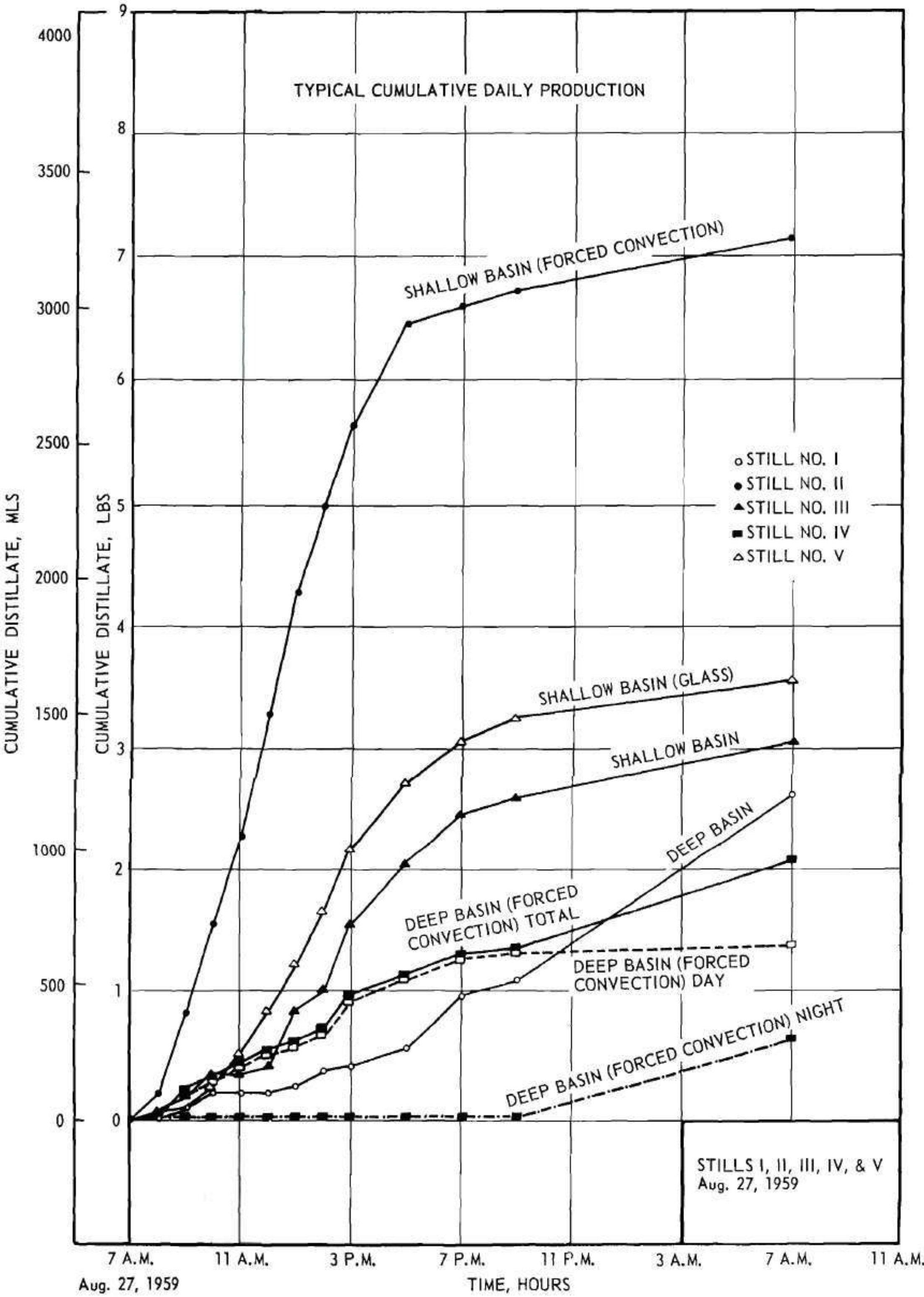



Figure 19.

**Typical Cumulative Daily Production**

daylight hours the transparent material has a higher temperature than ambient air. The reason is because transparent materials are exposed directly to the sun radiation, but ambient temperature is measured in the shade.

The results of data thus far obtained confirms the known fact that the yield increases as solar energy increases. Figure 20 in which the distillate from the Deep Basin still is plotted against solar energy shows a definite upward trend. Although the data is somewhat scattered, the best straight line fitted to this data by the method of least square shows a satisfactory coefficient of correlation, as exhibited by a value of $r = 0.53$. The equation of best fit, found by linear regression is:

$$q_f = 0.089 + 0.117H \tag{38}$$

where $q_f$ is distillate in lb/sq ft/day and H is in terms of 1000 BTU solar energy available. Scattering of data is expected as operational characteristics of solar stills.

It has already been pointed out that the daylight hours' production is very low. It was also shown in Table 6 that the lowest point of production is around noon. This is the region of maximum daily solar intensity. Therefore, it appears logical to assume that there exists an inverse relationship between daylight hours production and total solar energy available. Accordingly as shown in Figure 21 a plot of distillate in daylight hours against solar energy indicates a negative slope as might be expected. The straight line of best fit to these data is:

$$q_f = 0.131 - .0117H \tag{39}$$

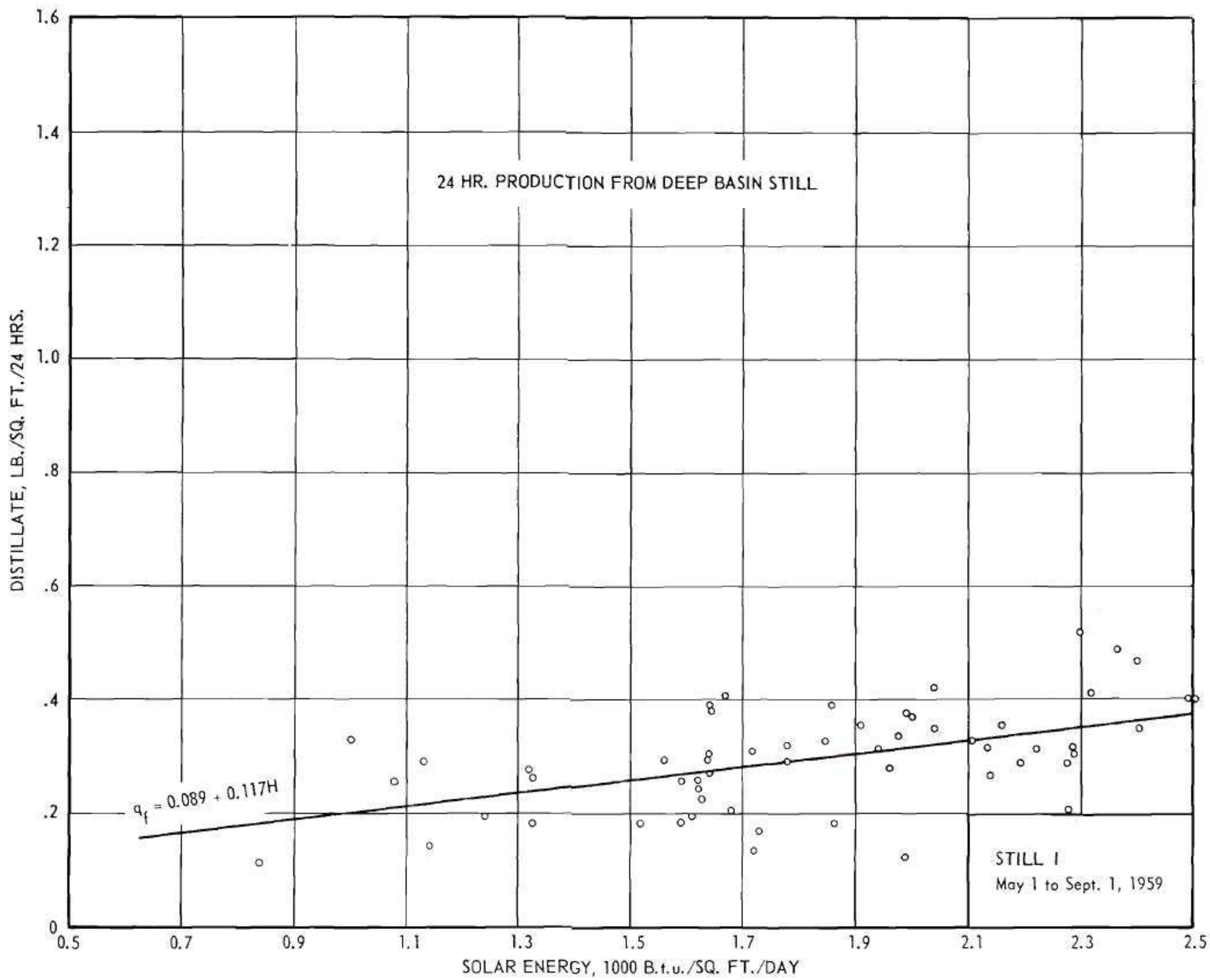



Figure 20.
**24-Hr. Production from Deep Basin Still**

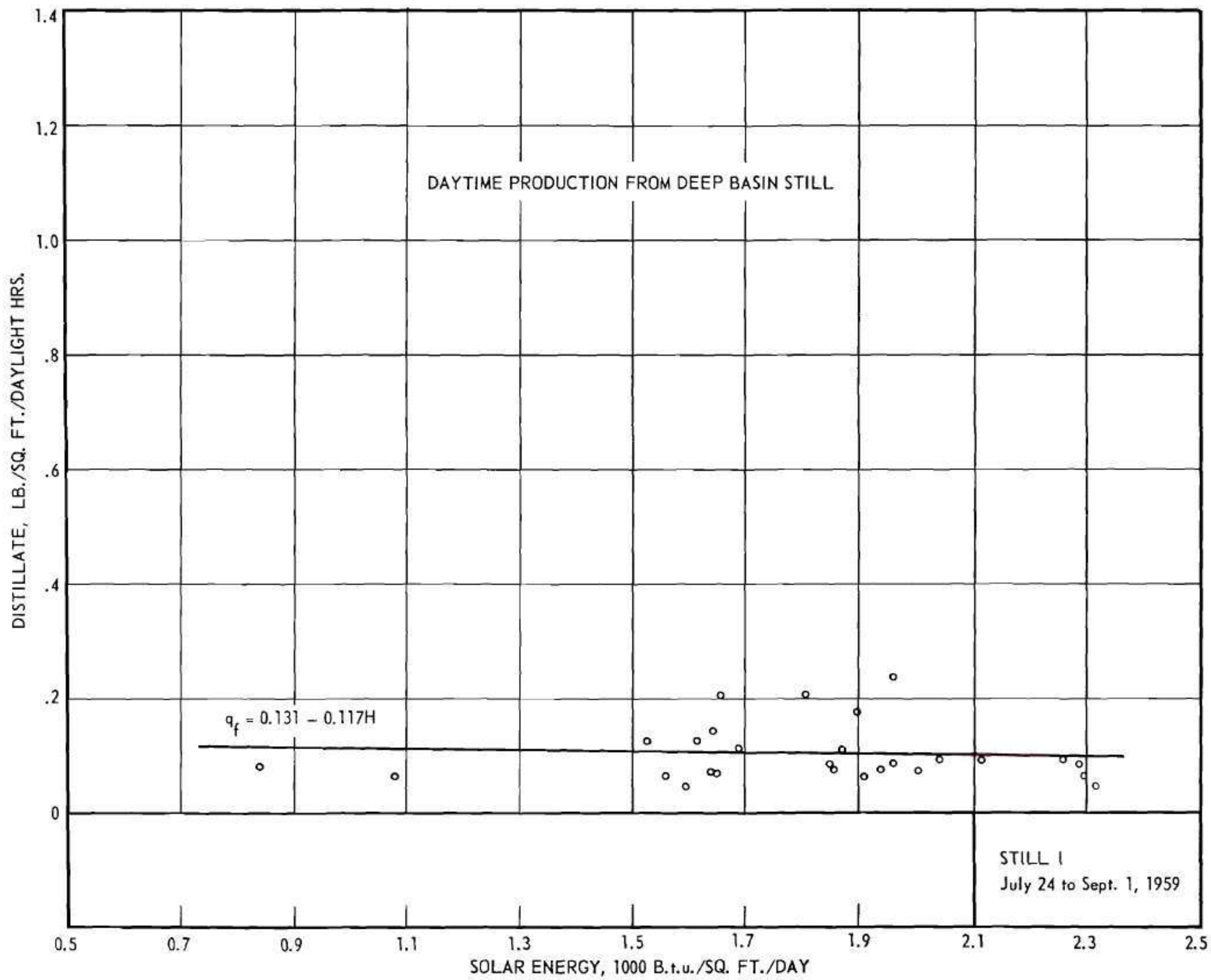



Figure 21.
Daytime Production from Deep Basin Still

However, the value of this negative slope is small enough that for all practical purposes it is possible to state that daylight hours production is independent from solar energy for values between 800 to 2500 BTU/sq ft/day.

Figure 22 reveals an interesting fact concerning the ability of a unit of solar energy to produce fresh water at different available energy levels. In this figure lb/sq ft/1000 BTU for each day is plotted versus solar energy reported by the pyreheliometer for the same day. The best straight line fitted to these points is in the form of:

$$q_f = .209 - .023H \tag{40}$$

having a negative slope. Theoretically, this line of best fit shows that each 1000 BTU is more effective in the lower energy band. It could be explained if it is considered that when the solar intensity is highest around July the ambient temperature is at a higher temperature relative to water, therefore less difference between air and water temperature, $t_w - t_a$, exists. Again, the negligibly small value of slope permits the assumption that efficiency of 1000 BTU is the same within the limited range of between 800 to 2500 BTU per day experimental points.

To study the effect of insulation on the operation of the deep basin design, the collector-evaporator unit of the Deep Basin (forced convection) unit was placed into operation as a control prior to insulation and forcing air through it. Since both designs are identical, any difference in operation must be attributed to the effect of insulation. Examination of Figures 23 and 24 in which hourly variations of water and air temperature (sensing element inside the still) are shown reveals

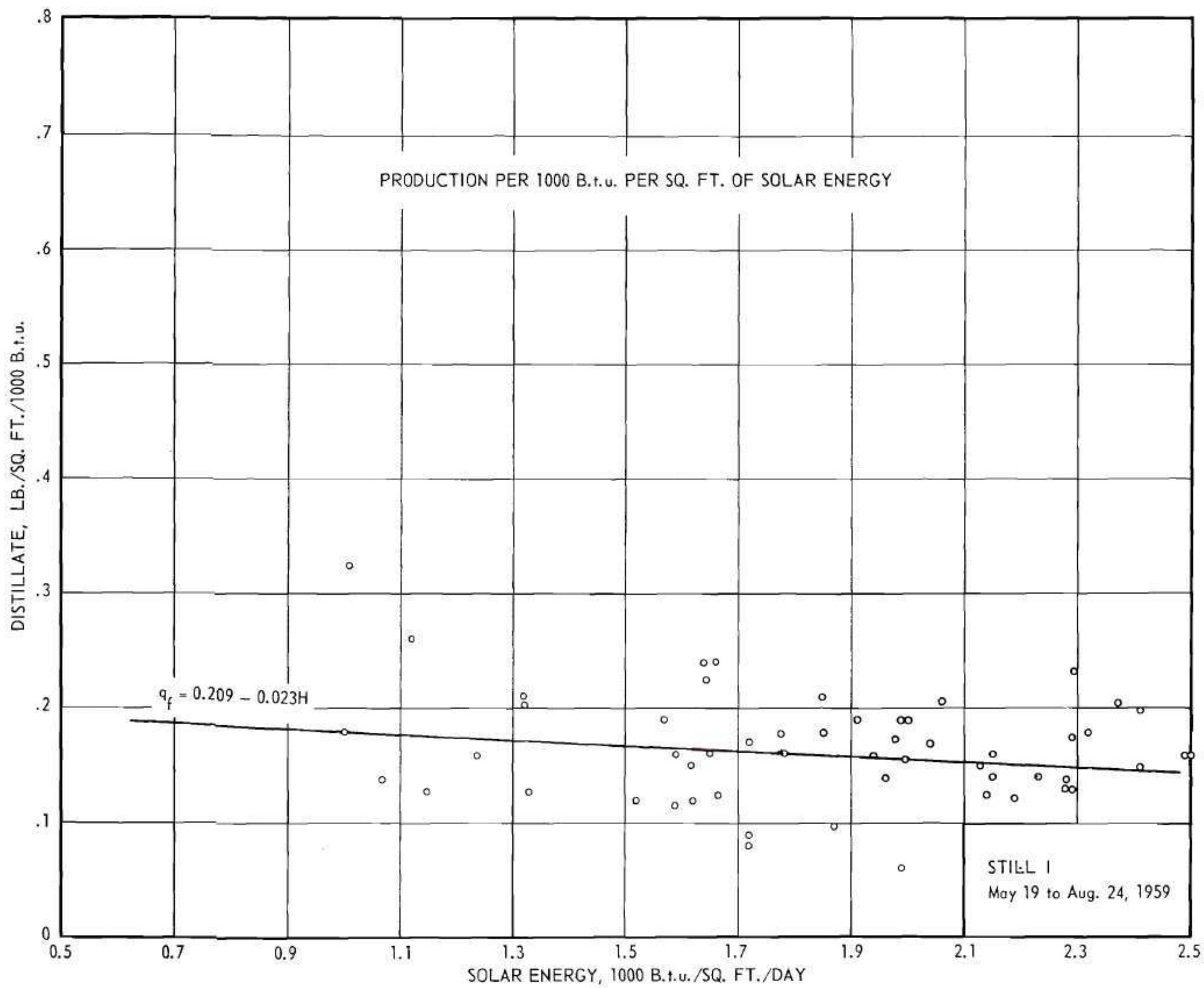



Figure 22.

**Production per 1000 BTU per sq ft of Solar Energy**

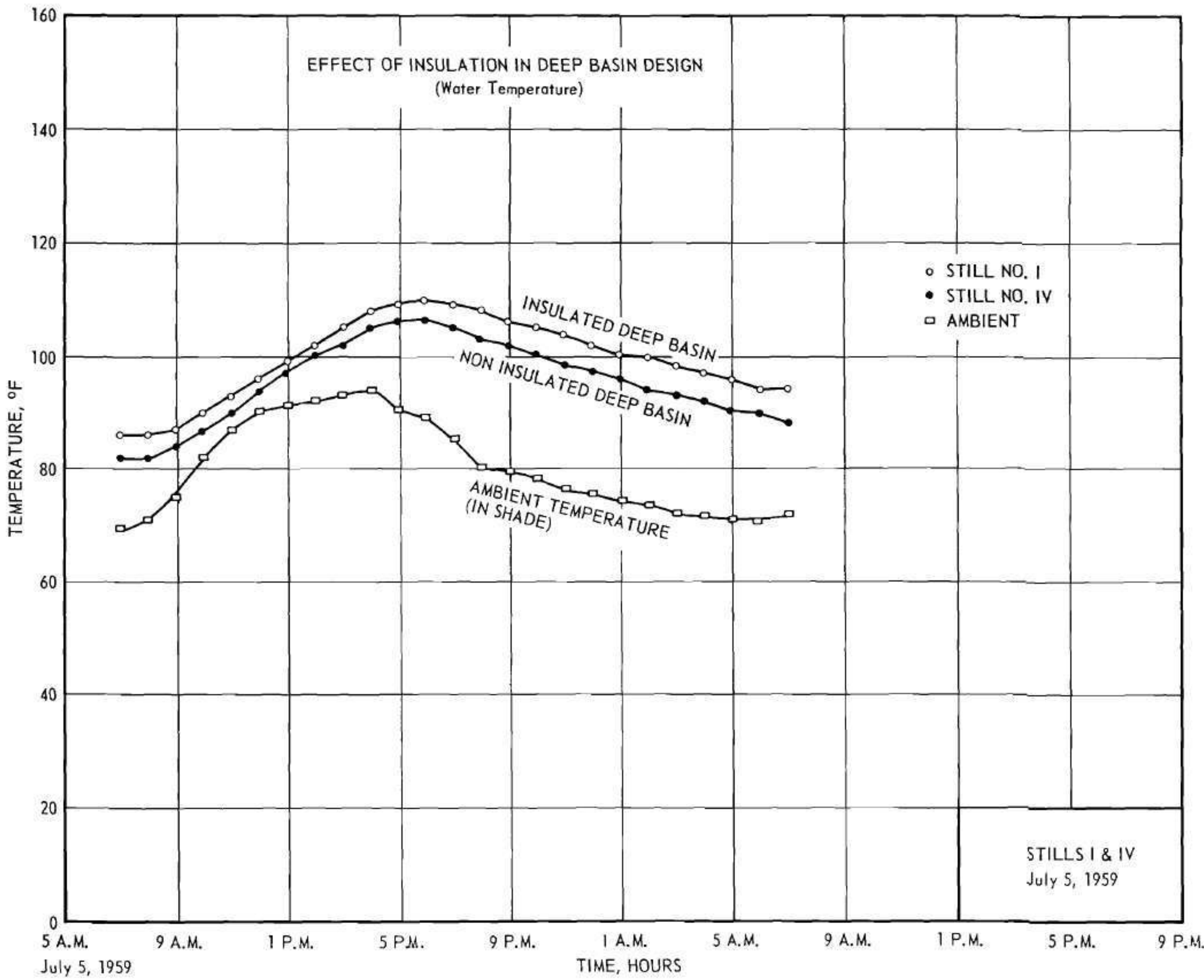



Figure 23.

**Effect of Insulation in Deep Basin Design (Water Temperature)**

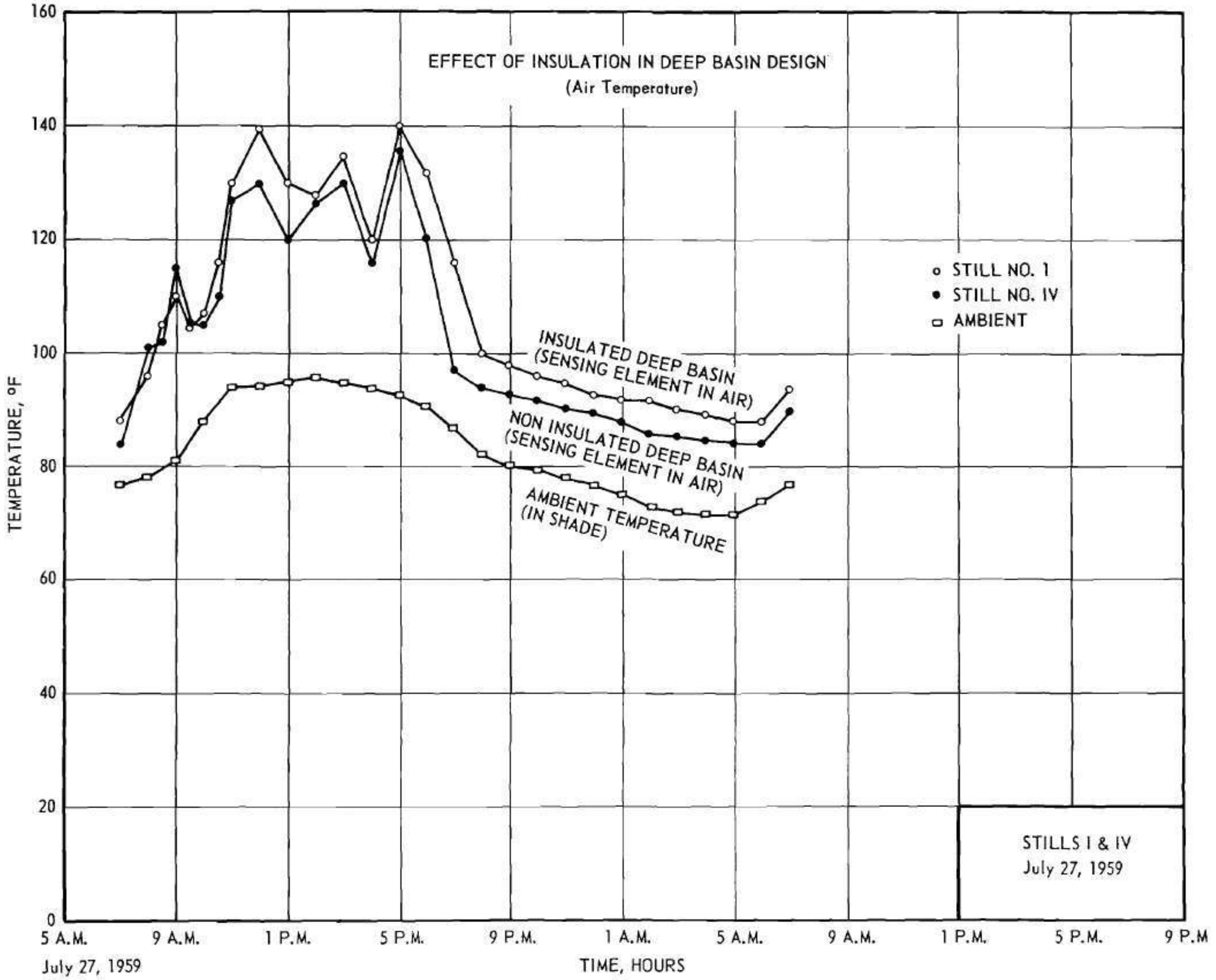



Figure 24.

**Effect of Insulation in Deep Basin Design (Air Temperature)**

that the non-insulated deep basin (Still IV operates at the higher temperature. Both cooling down and heating up of the non-insulated still happens faster.

In Figure 25 distillate from the non-insulated deep basin is plotted versus distillate for the insulated one for the same day. The straight line passing through origin with a slope of one is the line of equal production. Points on this line show that both stills produced equal amounts of distillate. Points above this line indicate that production from the non-insulated deep basin is higher than the insulated still, and points below this line indicate days when the production from insulated deep basin was higher. The straight line of best fit to the experimental data indicates that when production is below 0.265 lb/sq ft/day the non-insulated Deep Basin is superior but when it is above this value the production of insulated still is higher. Although at first this seems unreasonable, the apparent enigma may be explained by consideration of the fact that low water production corresponds to low available solar energy (according to Figure 24). When the solar energy is low the insulated deep basin operates at lower temperature. Therefore, the losses are negligibly small and insulation does not mean much. On the other hand, since these stills are built above the ground, the side walls introduce a variable in their behavior. In the insulated deep basin still, side walls effect is negligible, while in the non-insulated deep basin this effect accounts for some increase of the yield*. In the region of higher solar energy however,

*This means that for some period of daylight hours the temperature of water in the non-insulated deep basin must be higher than the insulated one. Unfortunately, there is no data available to support this.

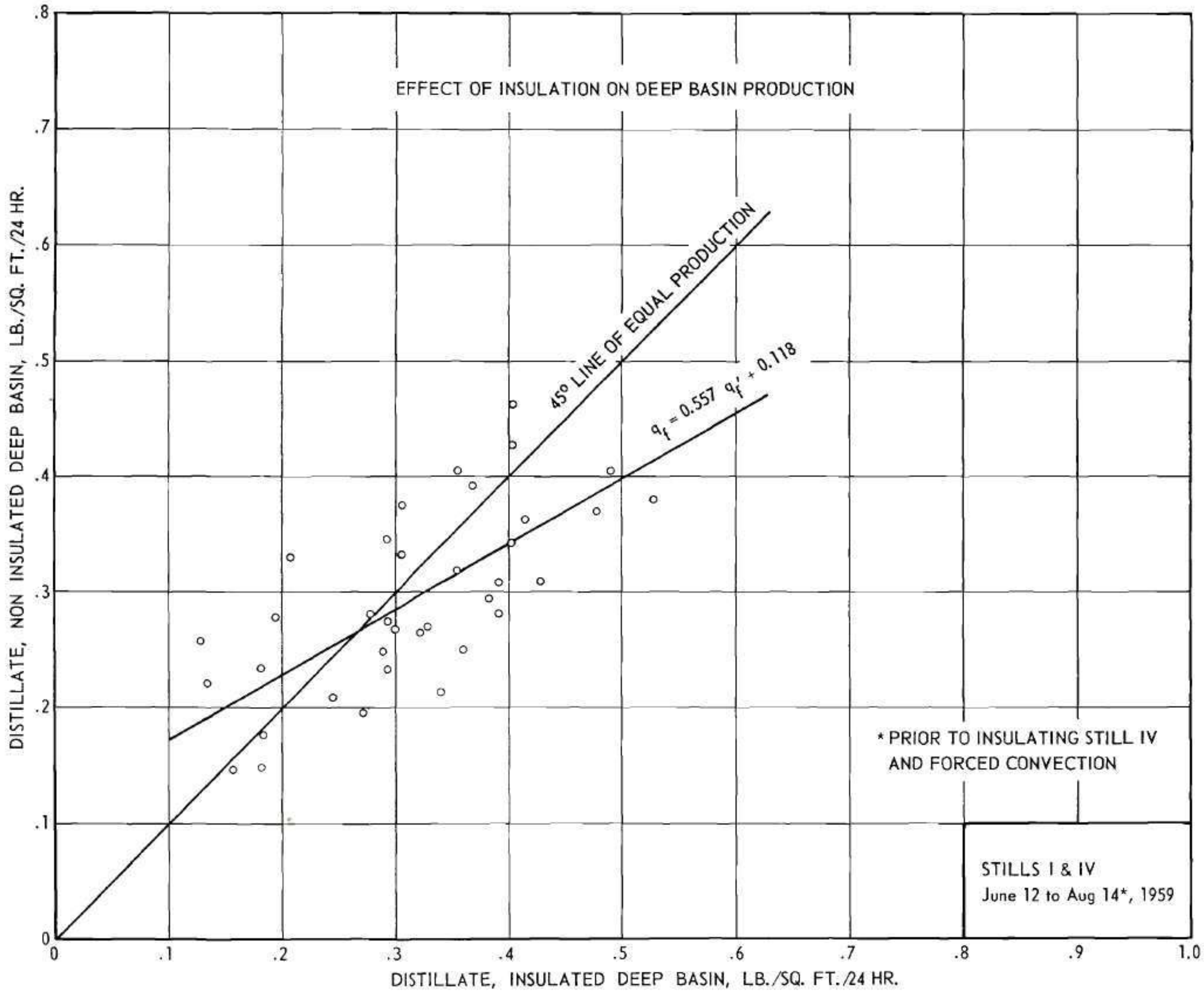



Figure 25.

**Effect of Insulation on Deep Basin Production**

the temperature of water is sufficiently higher so that heat losses are excessive and the effect of insulation becomes more pronounced.

Operational characteristics of Shallow Basin (glass).--Data available in the literature for the production from this type of still, designated "conventional still," is so varied that no realistic comparison is possible and it was therefore decided to test this type of still along with the other designs. The inconsistency of data reported is readily understandable because of so many uncontrollable factors which are involved. However, the general behavior of this design was found to conform closely with the reports cited in literature. Available data shows that production increases with solar energy. The straight line of best fit to the experimental data of distillate (in lb/sq ft/ 24 hours) plotted versus the total solar energy received (in 1000 BTU/sq ft/day), as shown in Figure 26, is in the form of:

$$q_f = 0.1 + 0.333H \tag{41}$$

To examine the scatter of data and establish their trend, the coefficient of correlation was found to have a satisfactory value of 0.54.

This straight line is in contrast with the deduction in Chapter III, from which a ceiling for production was expected, no matter how much solar energy is available. However, the solar energy during the four months of experimentation never exceeded the value of 2500 BTU/sq ft/day in Atlanta. If this value is exceeded the data might look different. Results of experiments in California reported by Howe (90) indicate that a ceiling value is approached between 2500 and 3000 BTU/sq ft/day. Figure 27 shows the relationshp between daylight hours production and solar intensity.

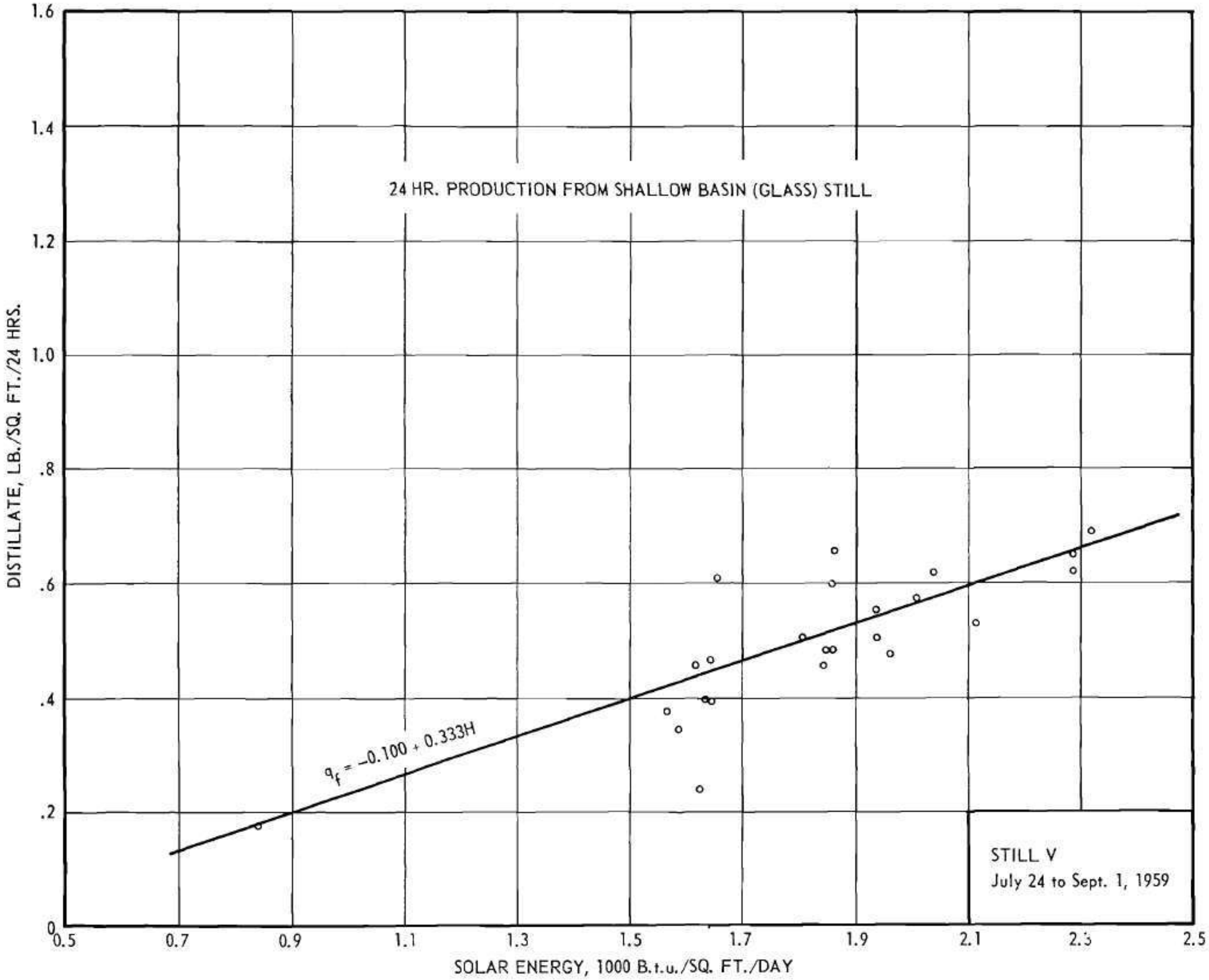



Figure 26.

**24-Hr. Production from Shallow Basin (Glass) Still**

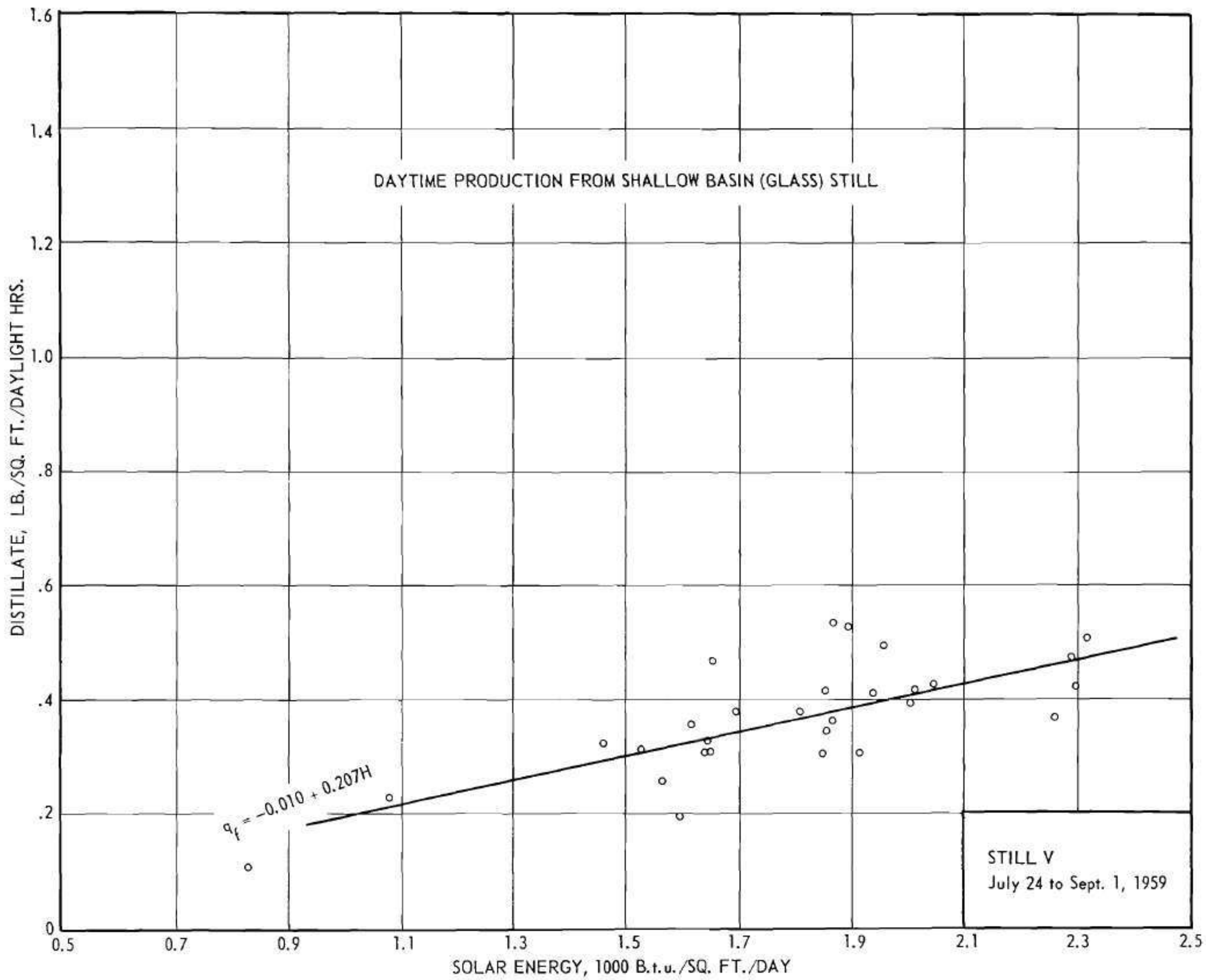


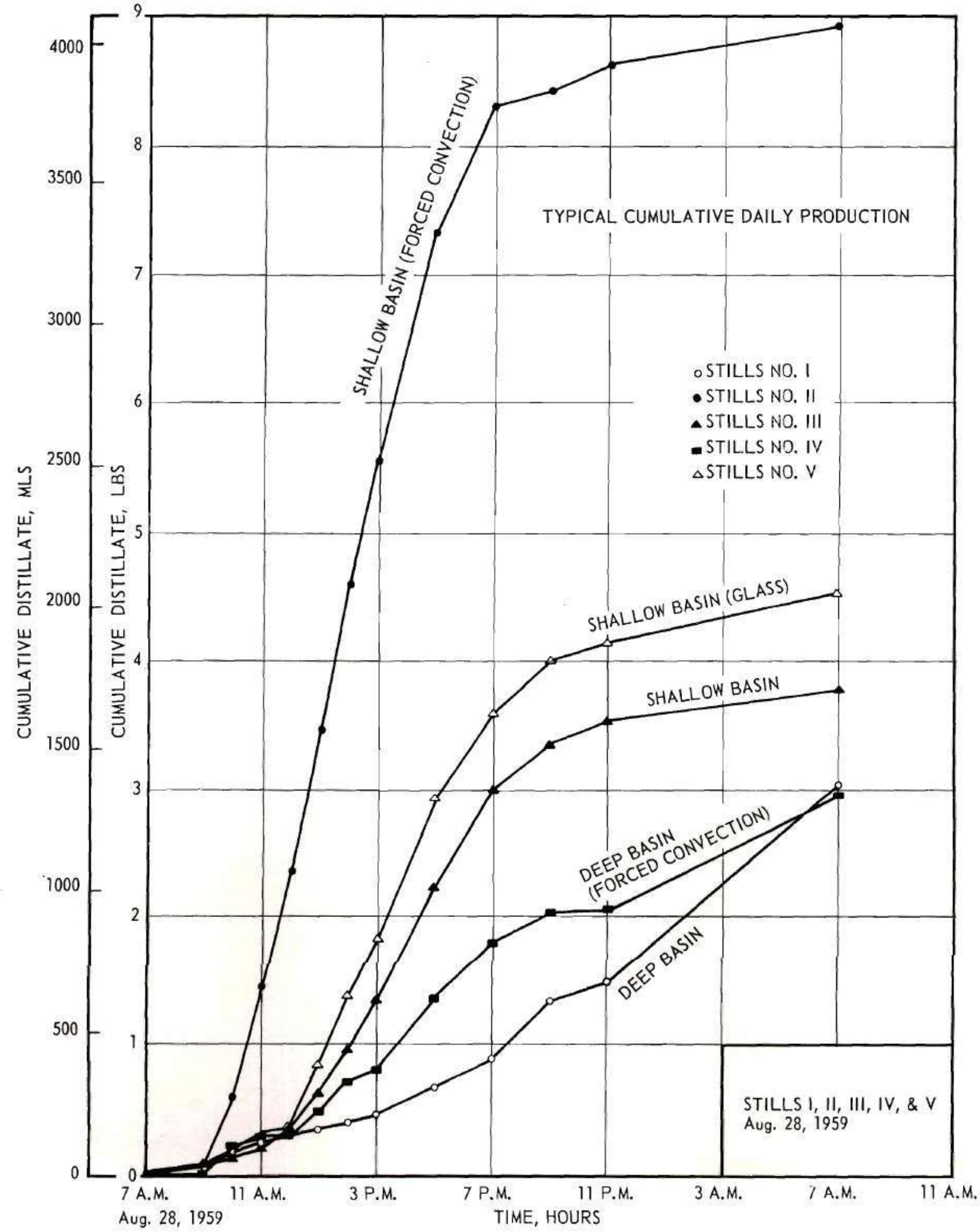

Figure 27.
**Daytime Production from Shallow Basin (Glass) Still**

Figure 28 indicates that production is very slow early in the day. It takes time for the cold body of water to heat up. Production at a higher rate starts around 12 a.m. and continues until 7 p.m. Afterwards, production again slows down until the next morning and actually ceases for all practical purposes for a brief period. During the experiments the highest water temperature $t_w$ reached was about 135 degrees F.

According to Figure 29 where distillate production for each 1000 BTU unit is plotted versus total solar energy (on that day) the efficiency increases as total solar energy increases. However, the slope of the best straight line of fit is very small and also the mass of data are below the region of the ceiling value. The coefficient of correlation $r = 0.39$ is not highly significant. Therefore, the foregoing conclusion about efficiency must be understood with its limitation.

Operational characteristics of Shallow Basin (forced convection).--This still designated as Still II, incorporates into its design the idea of separation between collector-evaporator unit from condenser. Forced convection is substituted for the natural convection present in the conventional design. Application of Mylar, type W, provides a simple light weight collector-evaporating unit. Complete lack of collecting troughs further simplifies the design, construction, operation and maintenance of this type of still.

In contrast with the deep basin, this still produces almost continuously during the daylight hours. A typical graph of cumulative hourly distillate is presented in Figure 28. The production is very small until 9 a.m. which represents the warming-up period and also a certain amount of distillate is required to wet the condenser surfaces before


TYPICAL CUMULATIVE DAILY PRODUCTION
SHALLOW BASIN (FORCED CONVECTION)
SHALLOW BASIN (GLASS)
SHALLOW BASIN
DEEP BASIN (FORCED CONVECTION)
DEEP BASIN
o STILLS NO. I
• STILLS NO. II
▲ STILLS NO. III
■ STILLS NO. IV
△ STILLS NO. V
STILLS I, II, III, IV, & V
Aug. 28, 1959
CUMULATIVE DISTILLATE, MLS
CUMULATIVE DISTILLATE, LBS
TIME, HOURS
7 A.M.
Aug. 28, 1959
11 A.M.
3 P.M.
7 P.M.
11 P.M.
3 A.M.
7 A.M.
11 A.M.
0
500
1000
1500
2000
2500
3000
3500
4000
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2
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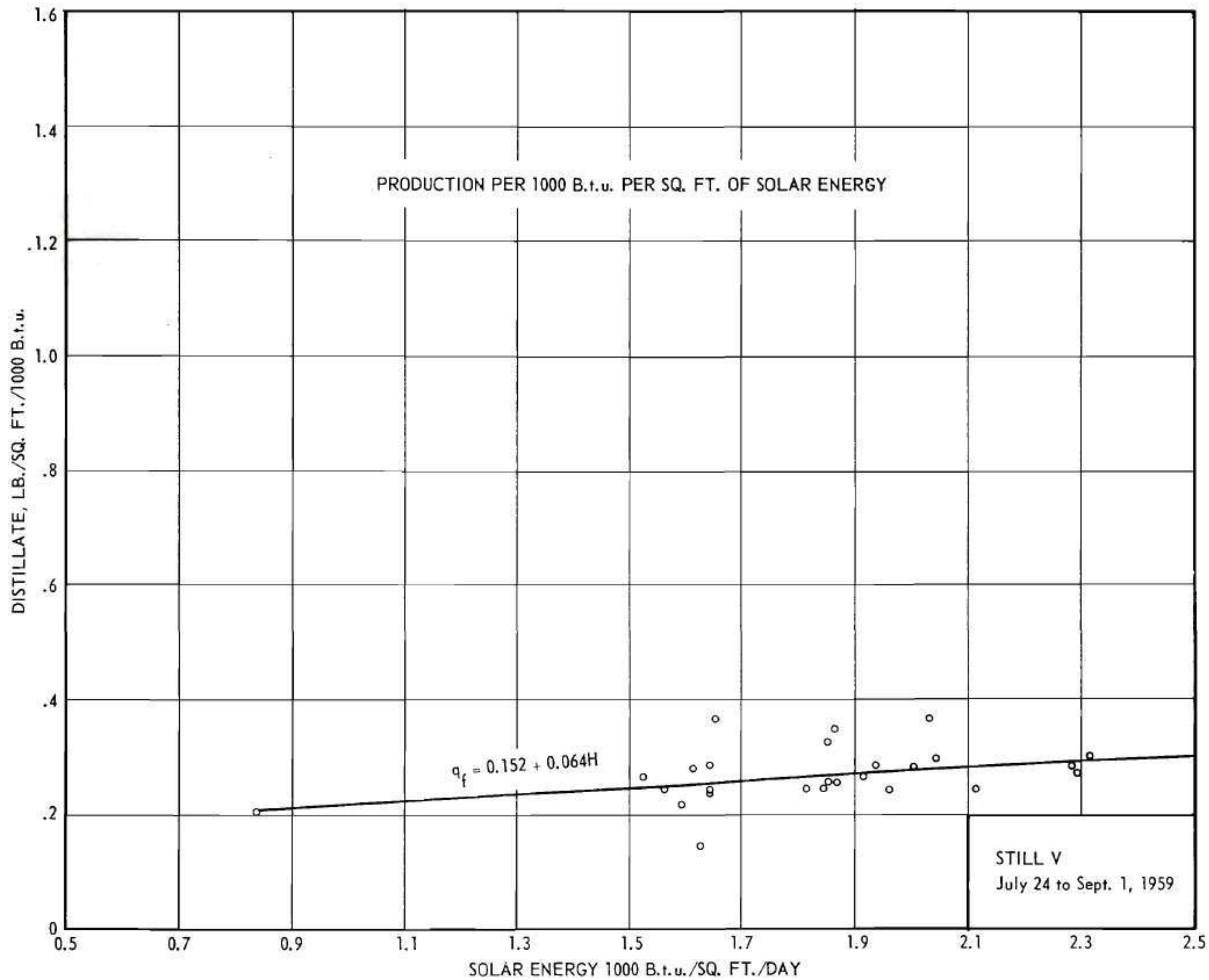



Figure 29.

**Production per 1000 BTU per sq ft of Solar Energy**

production appears and can be measured. After 9 a.m. production starts with a high rate which virtually remains constant until 5 p.m. and after that gradually slows down. The production during the daylight hours is almost 15 times greater than the night production. A great portion of the night distillate is probably the portion which remained in the condenser from daylight hours production and flows to the storage tank slowly during the night.

The collection and utilization of energy was found to be constant over the entire range of variation of solar energy during the experiments. Each 1000 BTU, statistically speaking, produces the same amount of distillate over the range of variation of the total solar energy. The line of best fit by linear regression to the adjusted distillate data based on 1000 BTU is plotted versus total solar energy (Fig. 30) and was found to have a slope of only 0.0016, or almost zero.

Data obtained within the experimental period shows very distinctly the relation between distillate and amount of energy which reaches the still. Figure 31 shows such a relationship. The slope of the line of best fit to the data is high and is equal to 0.503. The equation of the line is found to be:

$$q_f = -0.220 + 0.503H \tag{42}$$

with a reasonable value of the coefficient of correlation, $r = 0.42$. The improved efficiency of collection of solar energy was expected because the collector is mechanically separated from the condenser. This permits the continuous and proper functioning of collector under any type of atmospheric condition. Figure 32 shows the increase of day-

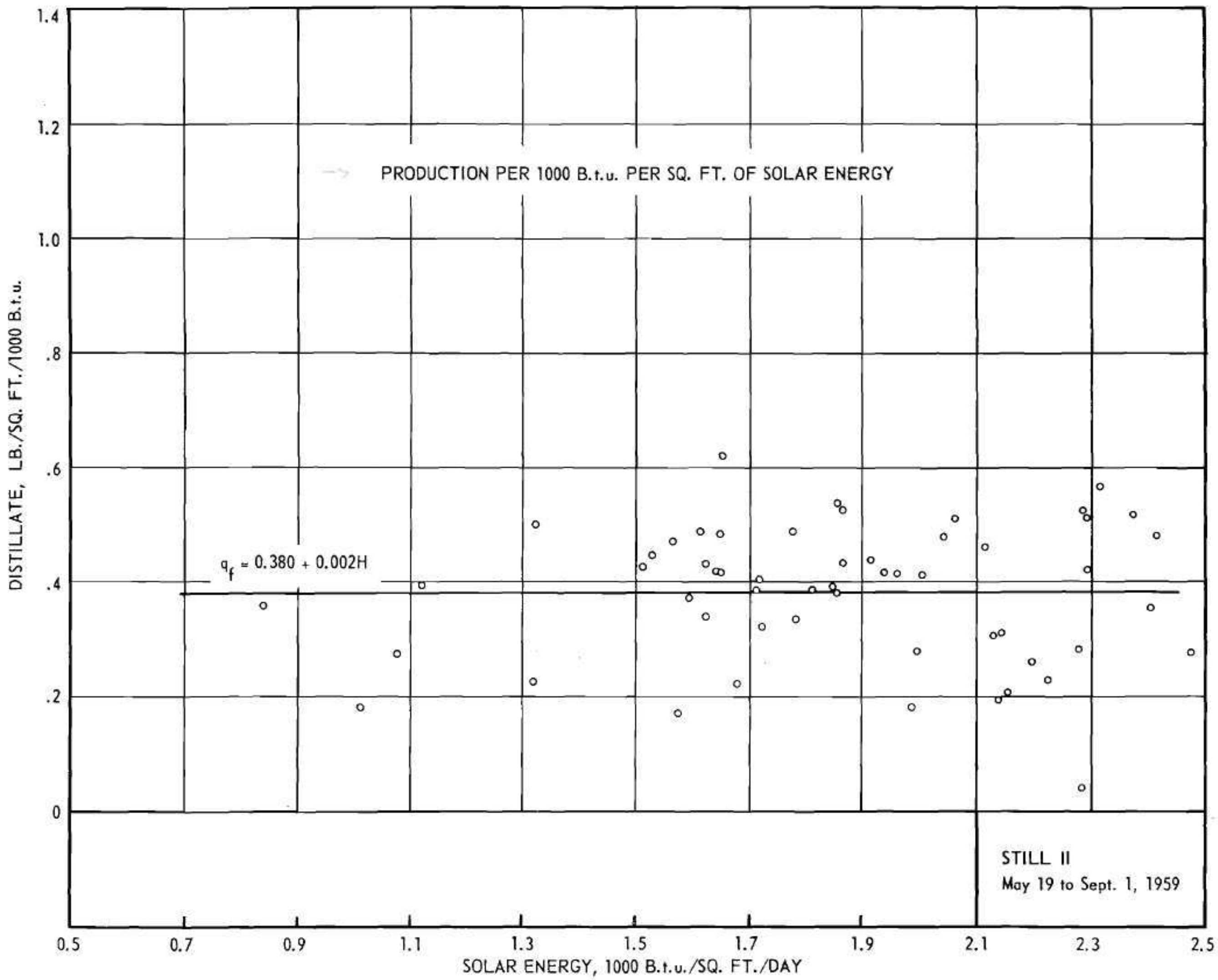
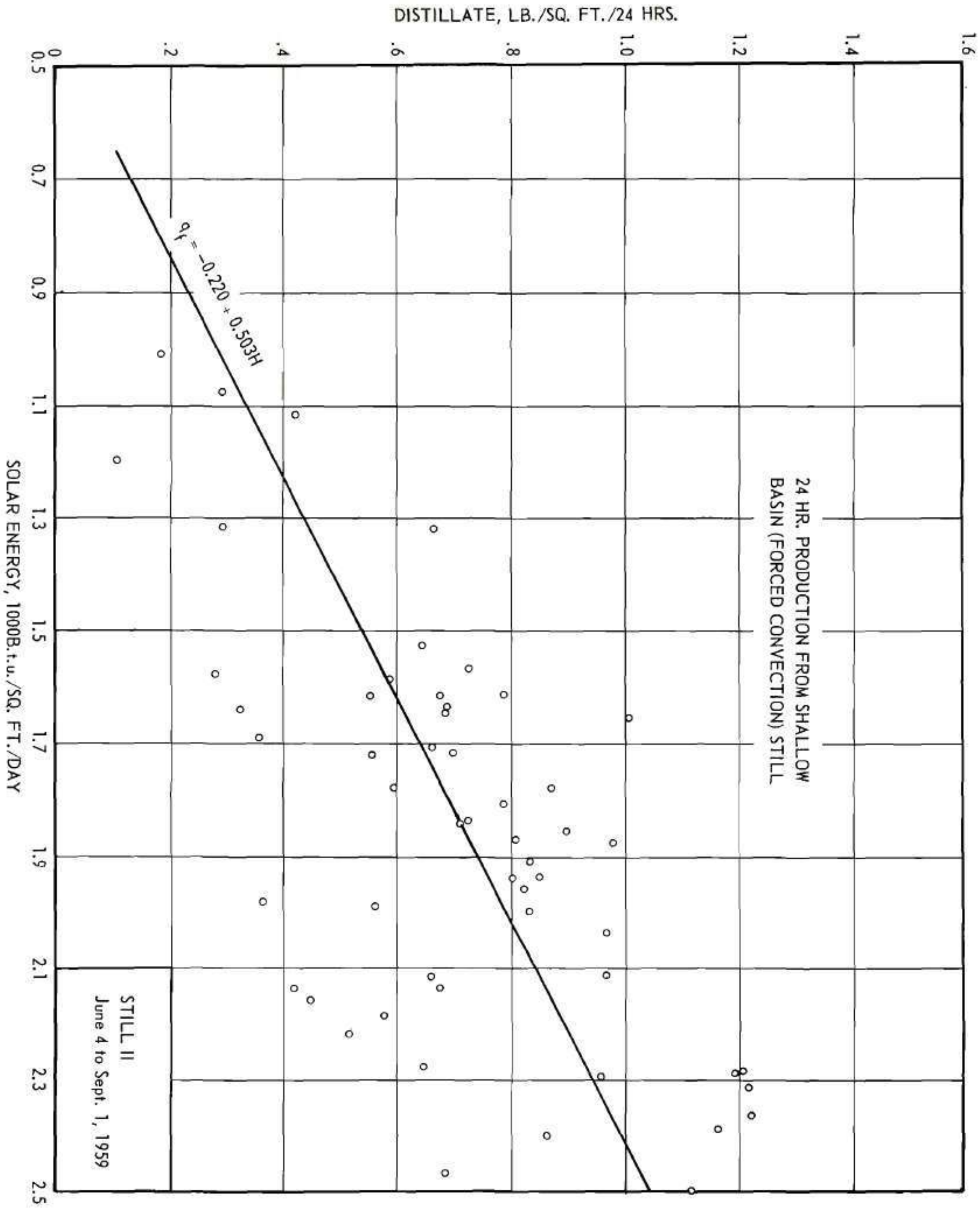



Figure 30.

**Production** per **1000** B.t.u. **Per Sq Ft** of Solar Energy


DISTILLATE, LB./SQ. FT./24 HRS.
SOLAR ENERGY, 1000B.t.u./SQ. FT./DAY
$q_f = -0.220 + 0.503H$
24 HR. PRODUCTION FROM SHALLOW BASIN (FORCED CONVECTION) STILL
STILL II
June 4 to Sept. 1, 1959
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5

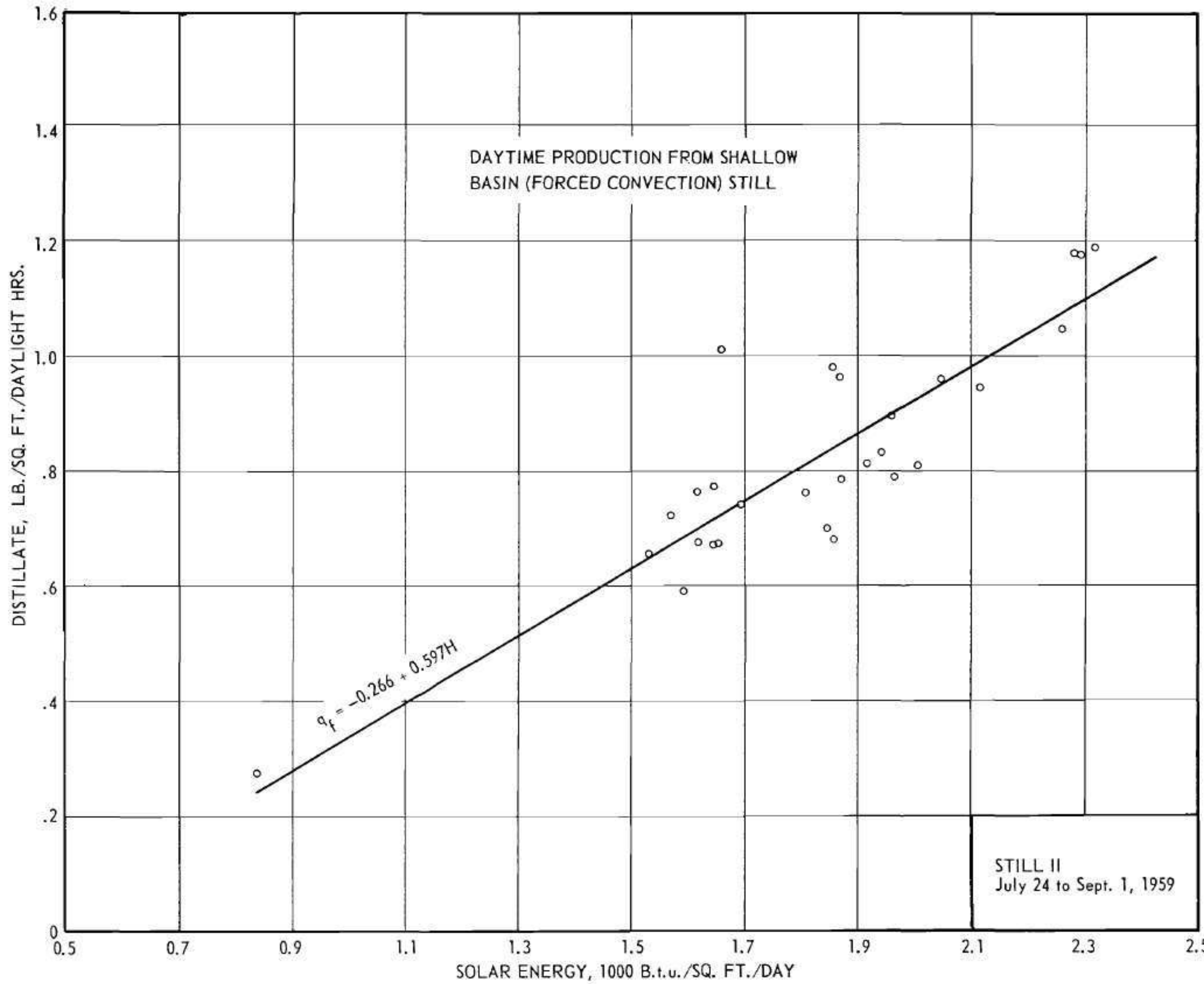



Figure 32.
**Daytime Production from Shallow Basin (Forced Convection) Still**

The distillate from the shallow basin (forced convection) still is the difference between water content of the saturated air at collector-evaporator temperature and saturated, cooled air leaving the condenser. Therefore, it was expected that both the amount of air passing through the system and the cooling effect of the condenser be most important in still operation. It is obvious that if the cooling capacity of the condenser is increased the temperature of the air leaving the condenser will be lowered. Therefore increased production could be expected. In this design air is functioning as the vapor carrier. Its capacity for carrying water is a function of temperature. The air that enters the system must be heated up to the still temperature. Therefore, if the air is already at a higher temperature before it enters the outside of collector-evaporator unit, it requires less energy to be heated up. Furthermore, for efficient operation this air must become saturated in as high a temperature as is possible with available solar energy. Consequently the relative humidity of the air as it enters the still is another important variable in the operation of this type of still.

The amount of air must be controlled to provide the most efficient use of the carrier. Experimentally this is accomplished by passing enough air through the still until only a very thin strip of condensate remained close to the effluent point of collector, indicating that the air leaving is saturated.

The effect which the amount of air has on production is shown in Figure 33. Different volumes of air were passed through the still on different days and the condensate adjusted on the basis of 2000 BTU/sq ft/day to eliminate the effect of the energy as a variable. The

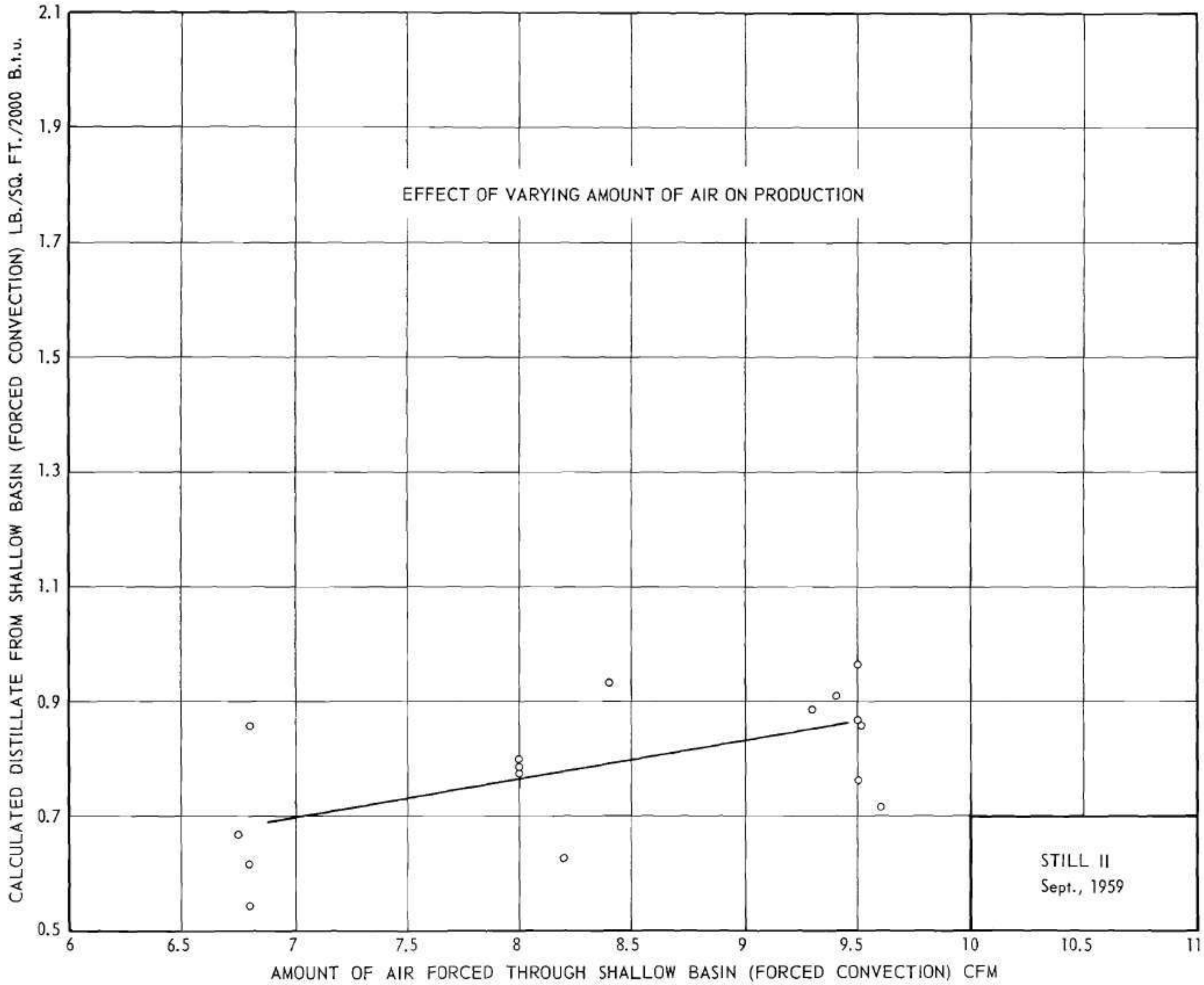



Figure 33.
**Effect of Varying Amount of Air on Production**

trend as indicated by the figure shows that the distillate per 2000 BTU is increased with an increasing air flow. At about 9 to 10 cfm appeared to be the best operating point. Beyond this value the strip of condensate disappeared. This curve shows only the trend. The proper value of air can be automatically determined by a humidity sensing element which can in turn control the flow of air. An excessive flow of air obviously would cool down the whole system and the production would drop off. When about 9 cfm of air (1 cfm per sq ft of area of collector) was passed through the system, the entire Mylar canopy was clear, but below this amount condensate was formed, increasing the reflection of Mylar considerably.

Operational characteristics of Shallow Basin (Still III).--The only difference between Still III and the conventional design is in the transparent roof material. Mylar, type w, was used in the construction of the roof for this still. The behavior of Still III closely follows the conventional design. Figure 34 shows the 24 hours production of this still versus solar energy. The equation for the line of best fit is:

$$q_f = -0.0638 + .239H \tag{43}$$

Figure 35 indicates the relation between daylight hours production and solar energy. A typical hourly production schedule is shown in Figure 19. It follows closely the production of conventional design, but is lower than Still V.

According to Figure 36, where distillate for each 1000 BTU unit is plotted versus total solar energy available the efficiency increases as total solar energy increases. However, the slope of the best straight line which has been fitted to these points is very small.

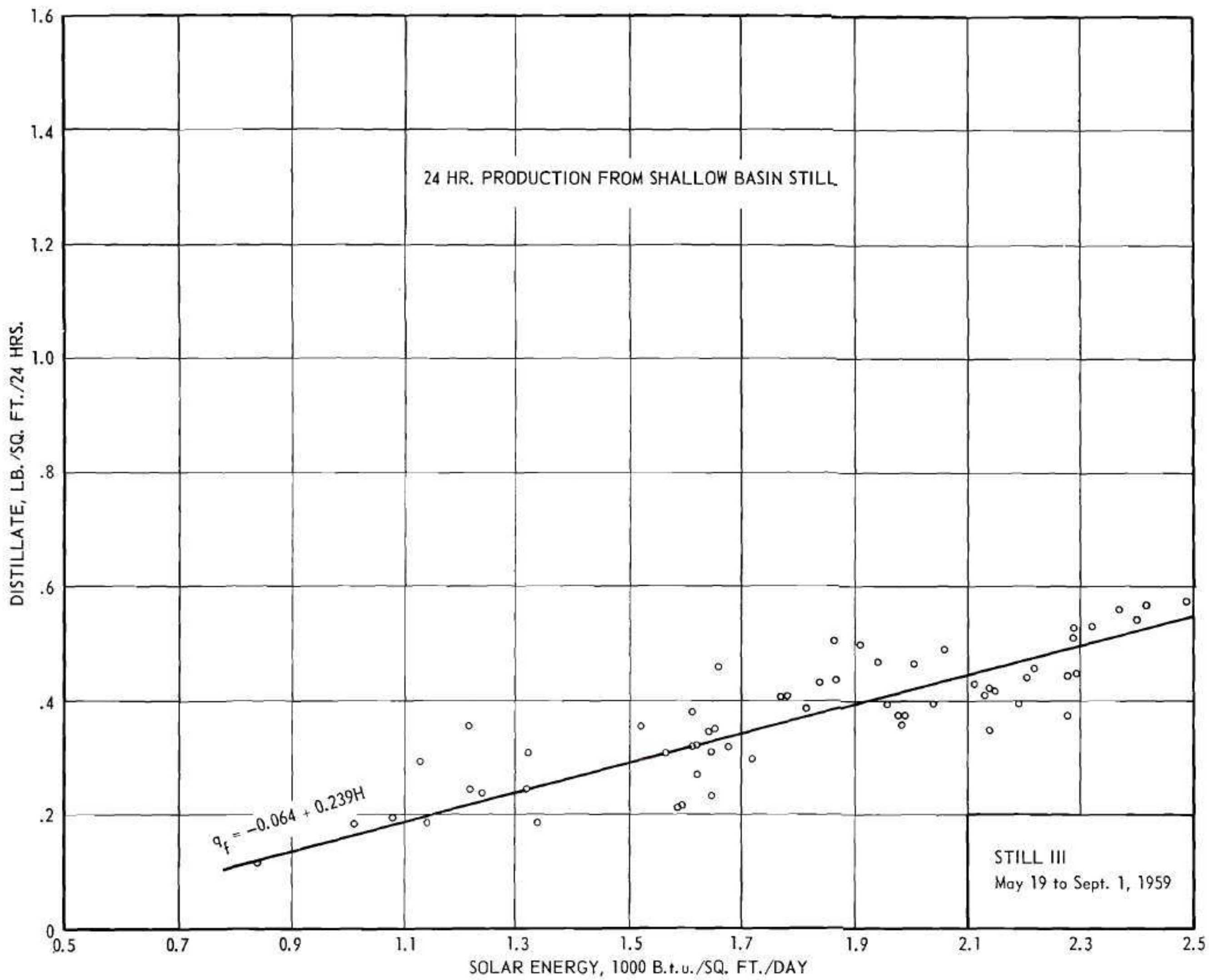



Figure 34.

**24-Hr. Production from Shallow Basin Still**

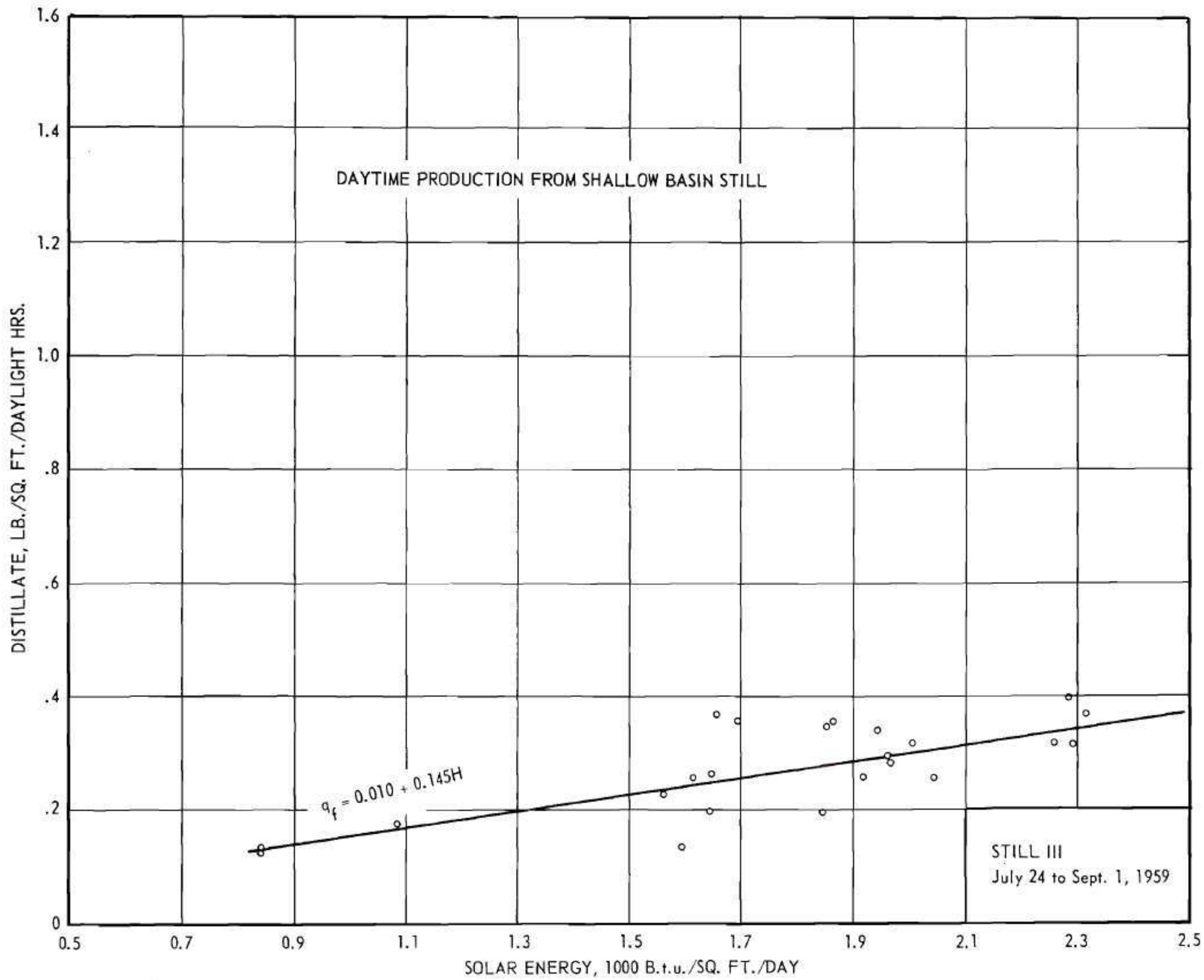



Figure 35.

**Daytime Production from Shallow Basin Still**

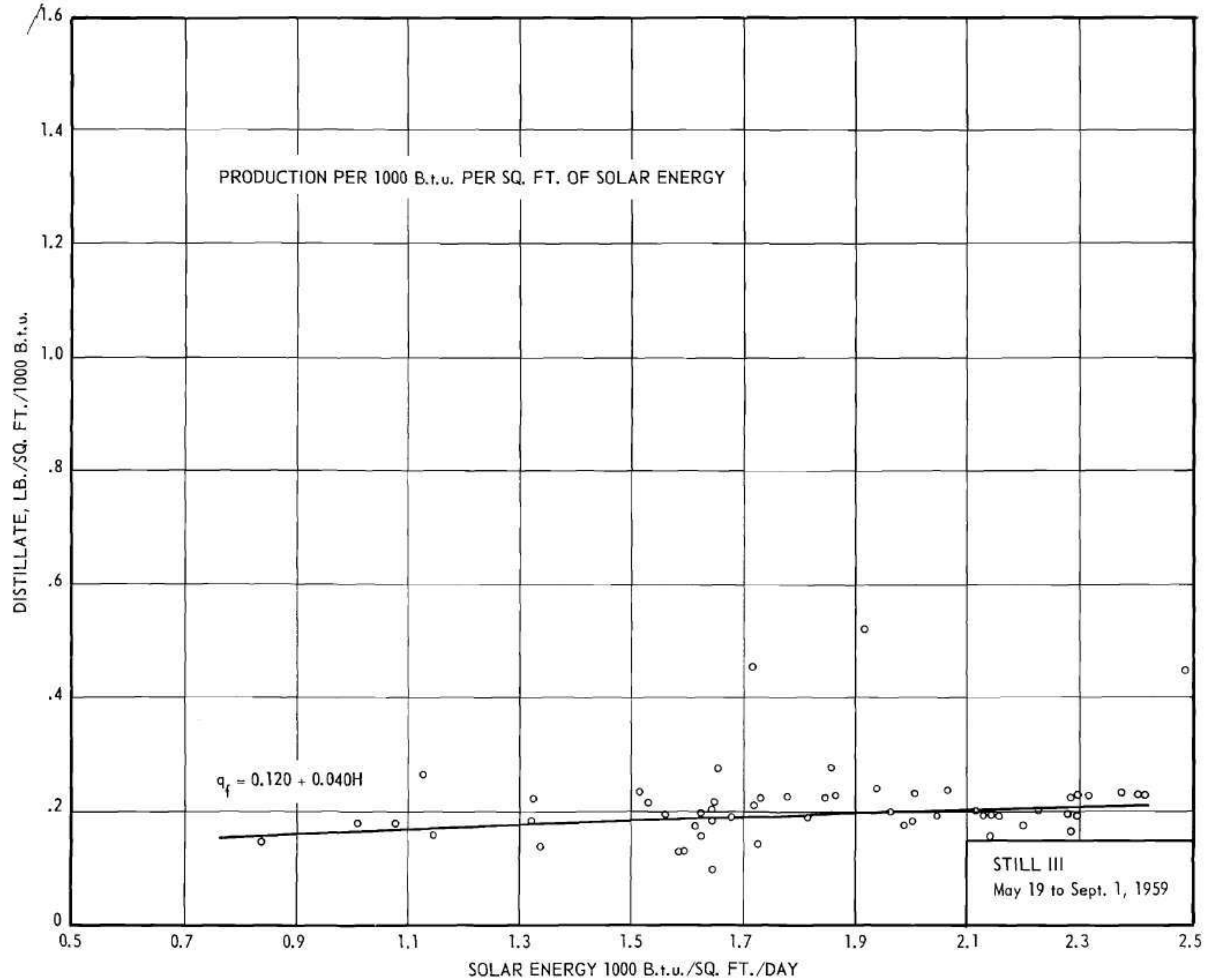



Figure 36.
Production per 1000 BTU per sq ft of Solar Energy

Operation characteristics of Deep Basin (forced convection).--This still, designated Still IV, was started on June 11, 1959, and operated under four different schemes. During the first two schemes it was operated with the top (variation 1) which is shown in Fig. 9 and is identical with Still I, III, and V. During the last two schemes (variation 2) was tested. In variation 2 a black perforated tray was mounted just inside the plastic canopy and above the basin. This design is shown in Fig. 15.

The four different operating schemes were as follows:

1. Prior to insulating the basin and forcing the air through it, the still operated on the principle of the Deep Basin design. It provided an excellent control for the evaluation of the effect of insulation in Deep Basin designs.

2. The basin was insulated and air was forced through the system. Under this system the operation was identical to the Shallow Basin (forced convection) Still. The heat exchanger worked merely as a condenser, its effluent was drained to waste. The condenser was cooled by excess water which had a temperature of about 73° F $\pm$.

During the daylight hours, air was blown at the rate of 7 cfm (at this rate the plastic cover was clear) and distillate was collected from the condenser. At 7 p.m. the flow of air was shut off and the condensate which was formed during the night under the Mylar roof collected from the troughs. A typical hourly production is shown in Fig. 19. The night distillate almost equals the daylight hours' production. Night production is from 9 p.m. to 9 a.m. (at this time the plastic became free from condensate), and daylight hour production starts. The blower was started at 7 a.m.

3. Shortly after the operation of scheme 2 began it was observed that due to the wall effect of the Deep Basin only a small portion of the sun's energy could be utilized. During much of the day the angle of the sun's rays are too small to reach to the black absorption bottom of the Deep Basin. To overcome this problem, the perforated black tray was installed. This design not only provided for more absorption of the sun's energy, but also permits the dispersion of the water in the form of a droplet shower. To operate scheme 3 a small water pump was installed to recirculate the water between the basin of the still and the top of the perforated tray.

The effect from the intermediate tray was quite noticeable and the improvement sizable. A typical, cumulative production based on hourly data is shown in Fig. 37. The full effect from the improvement may be appreciated when the production is compared with the conventional design both before and after the tray installation. Before installation of the tray, the production (Fig. 28) of the Deep Basin (forced convection) Still was 72 per cent of the conventional design, but it increased to 117 per cent after improvement, (Fig. 37).*

4. The fourth scheme was studied to evaluate the combined effect of all variation already discussed. Under this scheme the basin was drained at 7 a.m. The effluent from the heat exchanger was brought to the top of the perforated tray, and permitted to drop into the basin and accumulate there. At 5 p.m. the air blower and coolant water was cut off and the deep basin operation started. To store all incoming water in the basin, the flow had to be decreased considerably. The amount of air was adjusted to maintain a small strip of condensate at

*Fig. 37 shows the cumulative production of all stills on September 26, 1959. Shallow Basin (forced convection) Still operated with the rate of coolant water decreased considerably to evaluate the effect of the condenser.

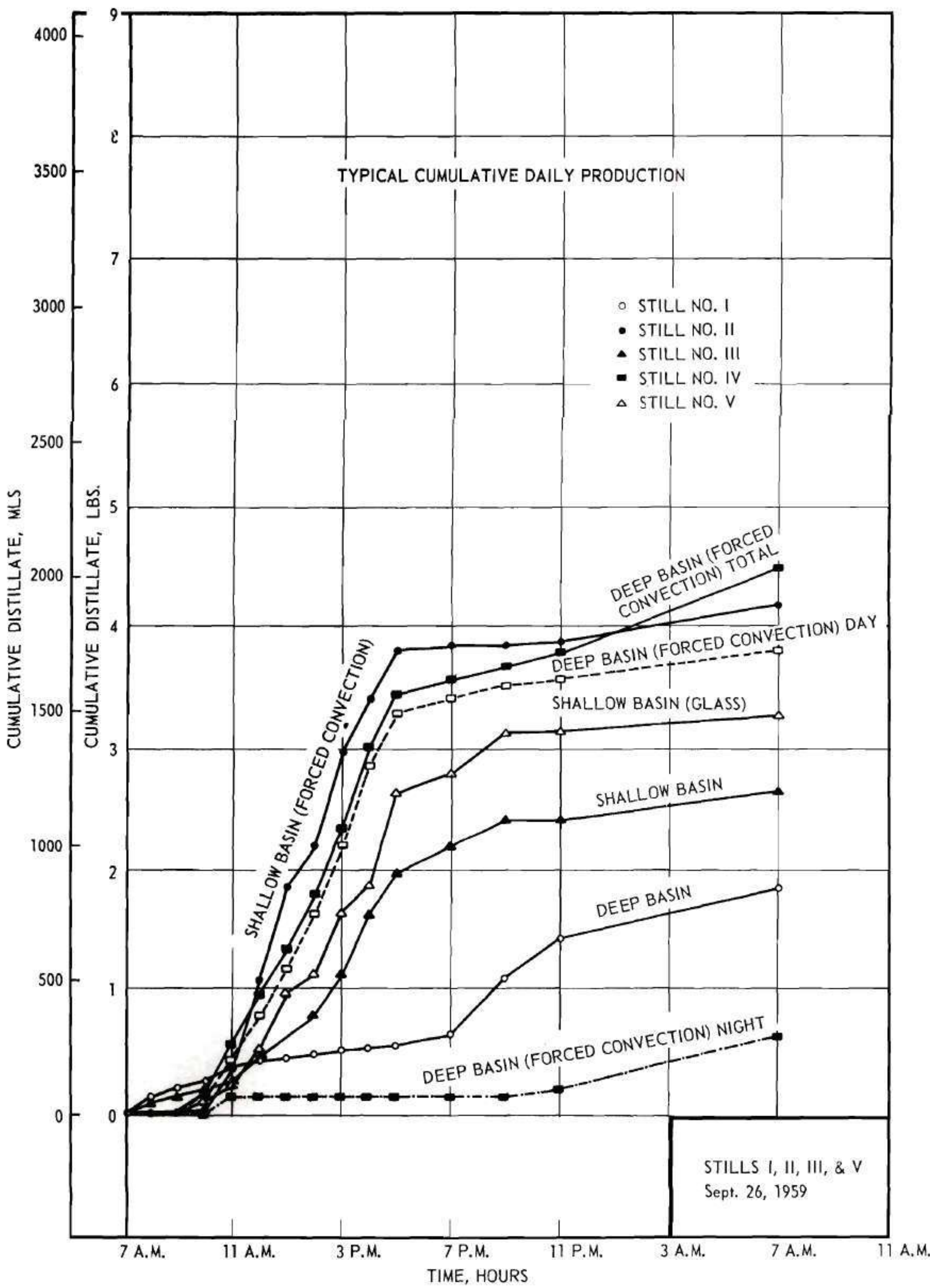
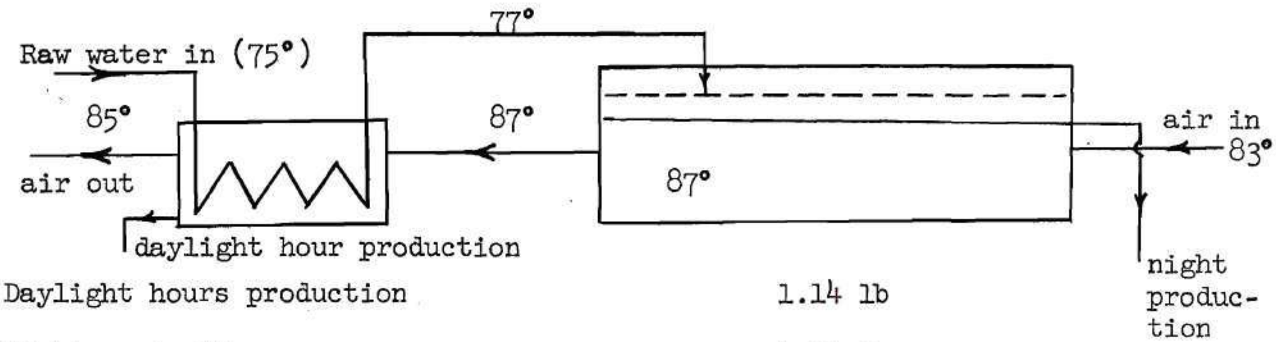



Figure 37.

Typical Cumulative Daily Production

the end of the Mylar canopy. Early the next morning the cold water, standing in the basin was drained and the next day's operation started. To evaluate the performance of this scheme, it is best to calculate data obtained from a typical day. The average temperatures in degrees F during daylight hours is shown in the sketch below.




| | |
|---|---|
| Daylight hours production | 1.14 lb |
| Night production | 1.03 lb |
| Total | 2.17 lb |
| Raw water entered | 499 lb |
| Relative humidity (average) ambient air | 58 per cent |
| Temperature of brine wasted at early morning | 75°F |
| Amount of air forced into still with 58 per cent relative humidity | 6156 cu ft/day light hour |
| Amount of dry air forced into still | 442.8 lb |
| Solar energy received | 1670 BTU/sq ft/day |
| Total energy received per nine sq ft still | 15034 BTU/day |
| Water content of air at 83°F and 58 per cent relative humidity | .01426 lb/lb of dry air |
| Total amount of water entered by air | 6.317 lb |
| Water content of air at 85°F and 100 per cent relative humidity | .02604 lb/lb of dry air |
| Total amount of water leaving the system in form of vapor in air | 11.536 lb |
| The amount of water that evaporated and wasted by leaving air | 5.218 lb |

| | |
|---|---|
| Heat of vaporization at 85°F | 1045.23 BTU/lb of water |
| Change of enthalpy of evaporated water | 5454.0 BTU |
| Change of enthalpy of incoming water (assuming night production leaves at 75°) | 0 BTU |
| Change of enthalpy of incoming air | |
| 1. water | 12.6 BTU |
| 2. dry air | 212.0 BTU |
| Change of enthalpy of day production | 11.0 BTU |
| Total enthalpy changes | 5788.6 BTU |
| Efficiency of collection | $\frac{5788.6}{15034} =$ 38.5 per cent |

The efficiency is low because the ratio of heat loss from piping to all systems is considerably high (none of the piping was insulated). Even more important is the fact that losses in this experimental still (nine sq ft) are much higher than actual prototype size plant. Another factor which contributes to this low efficiency is that the still is above the ground and heat losses through convection and radiation occur in all directions. Therefore an efficiency of collection of solar energy much higher than this value could be expected.

Even with this low efficiency of collection the production would be several fold (about eight lb, from eq. 48, Chapter IV) if heat exchanger would function properly. Actually the heat exchanger did not function at all. The reason for this deficiency is that the quantity of water which can be used with the nine sq ft model is relatively small, producing a velocity of only about .15 ft per second in the tubing of heat exchanger. Coefficient of heat transport is very small in this range. The problem will be overcome if larger area is used.

<u>Comparison of operational characteristics of different designs</u>.--Fig. 19 and Fig. 28 represent typical cumulative hourly production from all

stills. Deep Basin (forced convection) Still IV, operated on scheme 2. The superiority of production of the Shallow Basin (forced convection) is unmistakable. The higher production indicates the advantage to be gained from mechanical separation of the collector-evaporator and the external condenser, plus forced convection. This arrangement completely eliminates the effect of condensate on solar radiation collection and actually provides a better opportunity for condensation.

Shallow Basin, which differs from the conventional design only because its roof is formed by a transparent material, Mylar, produces somewhat lower than Shallow Basin (Glass). The lower production is due to the form of condensation. When the glass is clean the condensate forms a sheet which is quite transparent to solar energy. But in the case of Mylar condensates are developed in the form of drops. The droplet formation increases the reflective property of Mylar and it acts somewhat like a mirror. The efficiency of transmission of solar energy then becomes very low. Although the dropwise condensation is more efficient than sheet condensation the net effect is lower production for a plastic cover still, which may however still be more economical.

Fig. 38 compares the distillate from Still II and III. The line with a 45° slope which passes through the origin indicates the equal production. Points above the 45° line indicate the greater production of Still II. The upward trend in the line of the best fit shows the definite superiority of Still II in higher range of solar energy. Fig. 39 shows essentially the same thing as Fig. 38, only it compares Shallow Basin (forced convection) with the Conventional design, Still V.

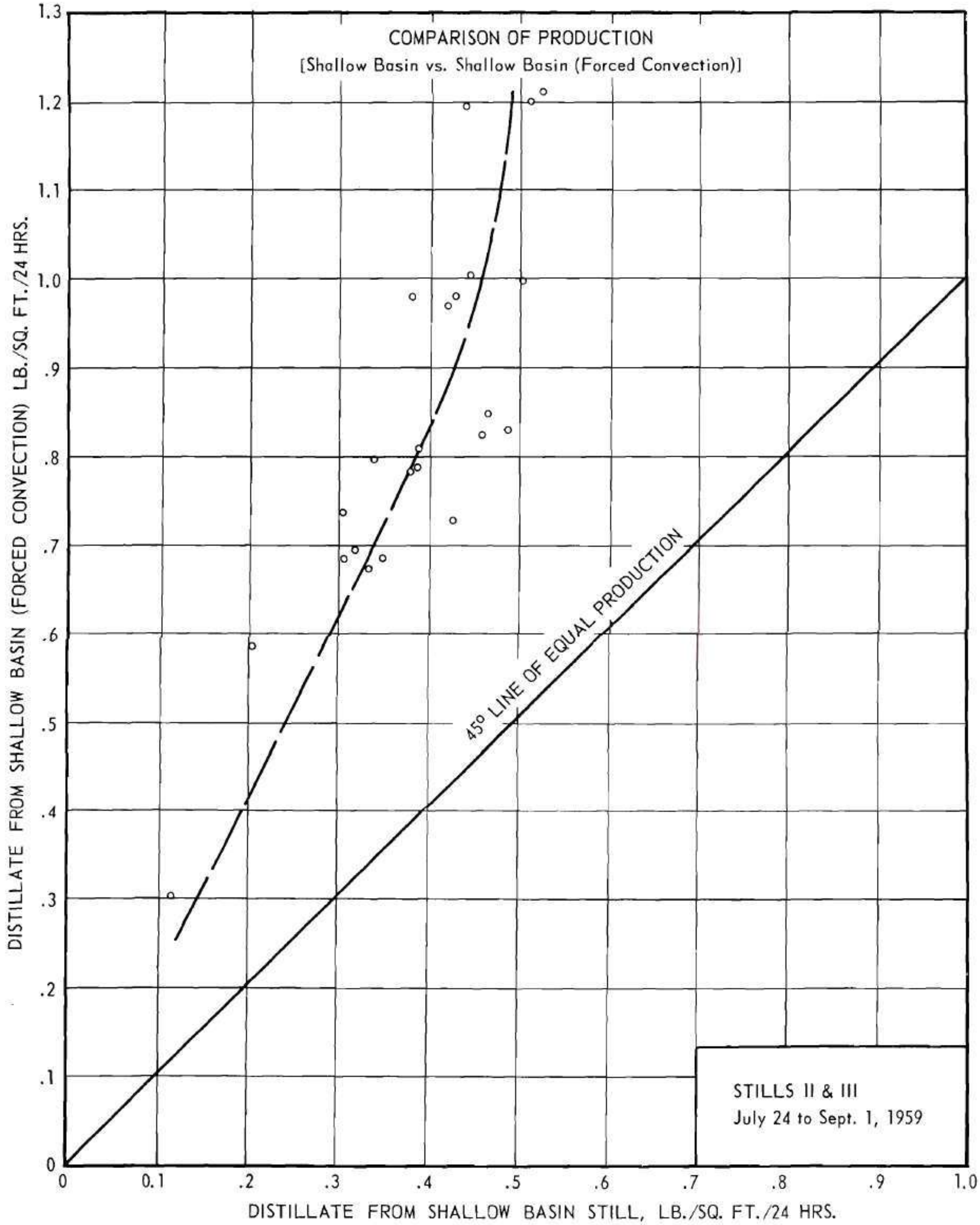



Figure 38.

**Comparison of Production**
**[Shallow Basin vs. Shallow Basin (Forced Convection)]**

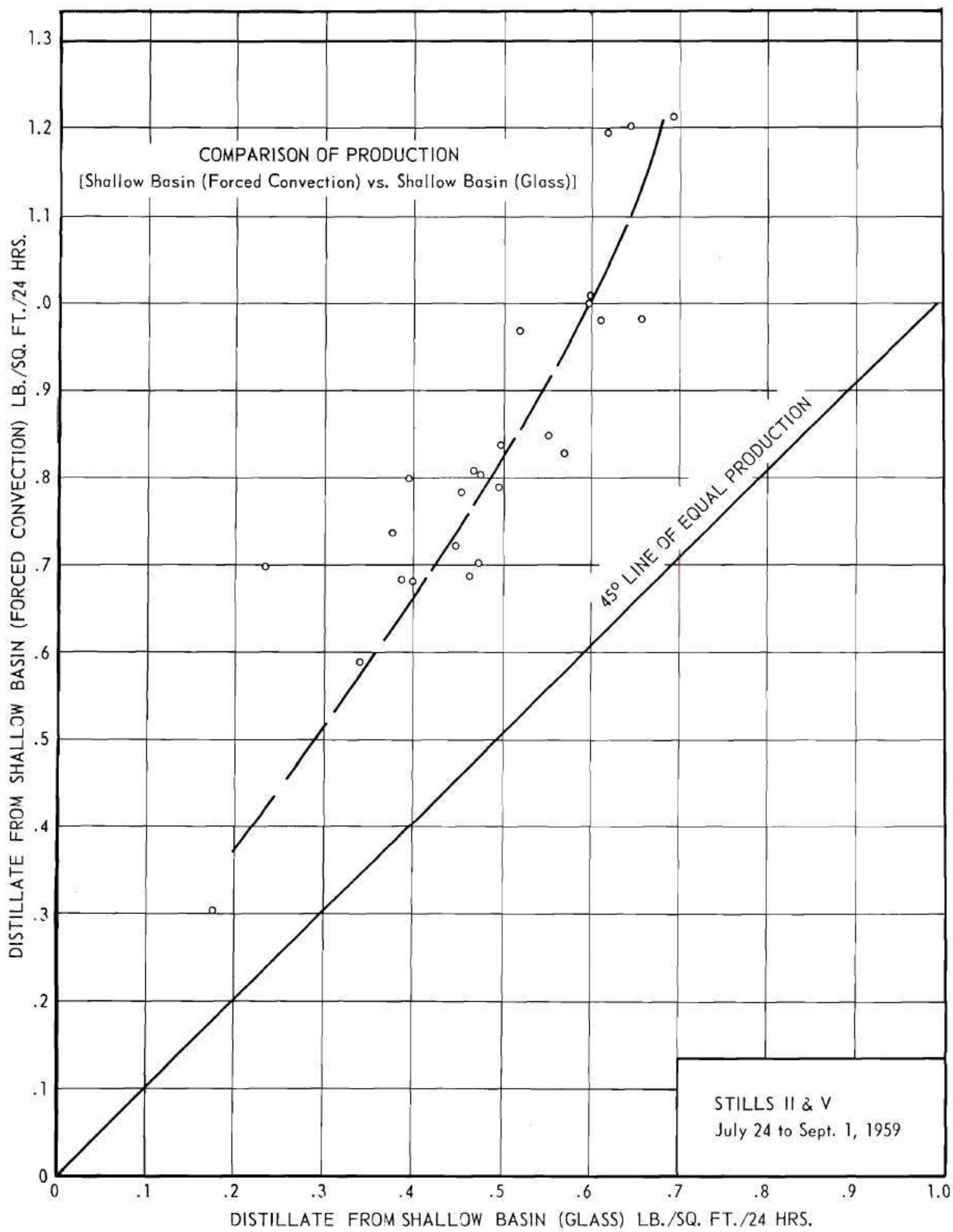



Figure 39.

Comparison of Production
[Shallow Basin (Forced Convection) vs. Shallow Basin (Glass)]

Deep Basin definitely produces less than the other but this could be due to the size of the experimental setup. The size of the stills is so small that wall effect is important. The effect is more pronounced in the Deep Basin stills where during much of the day the sun's rays cannot enter the basin.

The same relative production is maintained over the range of variation of solar energy. Fig. 40 represents all lines of best fit to the data of 24 hour production or daylight hour production plotted versus solar energy. The production line of Still II lies above all others. The line of best fit to daylight hours distillate for all still and the total for Still V are found from data obtained from July 24, 1959, to September 1, 1959, but total production for Stills I, II and III is from data obtained from May 19, 1959, to September 1, 1959. This explains why the "day" line lies above total in Still II.

The possibility of decreasing the slope of the best fitted line to data for Conventional Still in the range of solar energy higher than 2500 BTU/sq ft/day was discussed before, however there is no reason to think that the same will happen for the Shallow Basin (forced convection) Still. Therefore, it may be that in the region of the higher solar energy the relative production of Still II is even higher.

In Fig. 41 the distillate from the Conventional design is assumed to be 100 per cent and the percentage of production from other stills is plotted against solar energy. The figure presents the relative production compared to the Conventional design. Shallow Basin (forced convection) is produced on the average about 170 per cent more than conventional. The values lie between 143 and 200 per cent. Shallow

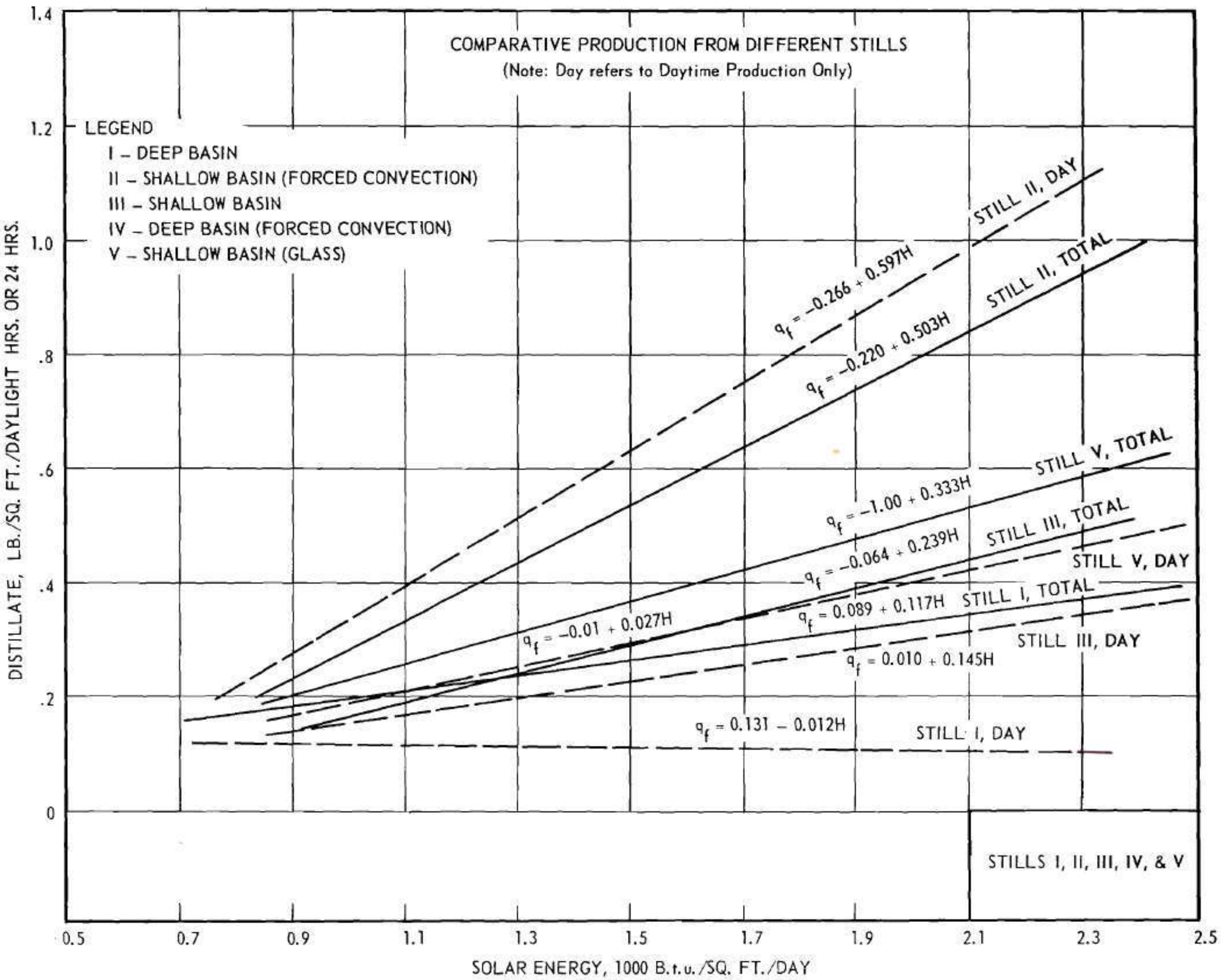



Figure 40.

Comparative Production From Different Stills

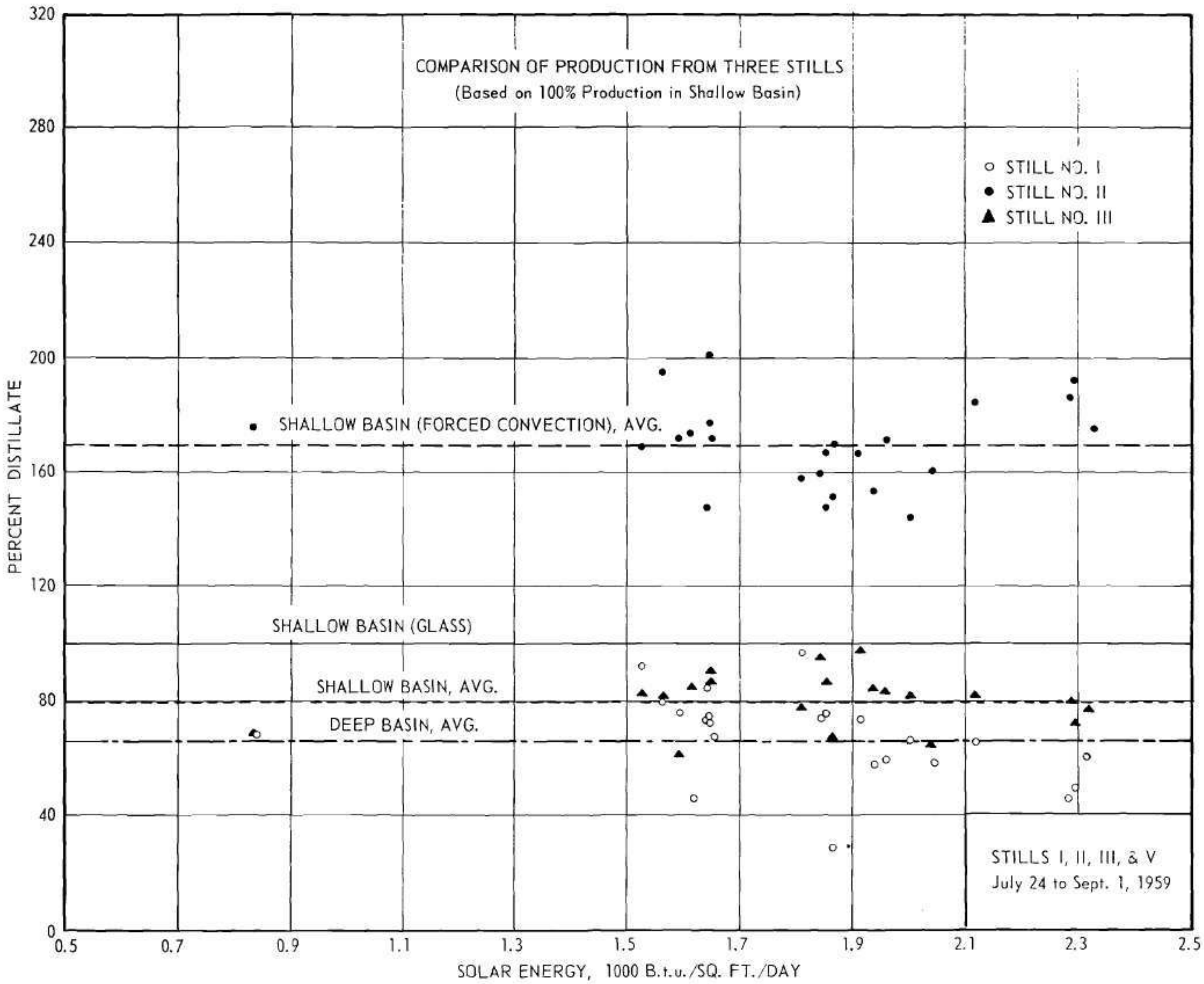



Figure 41.

**Comparison of Production from Three Stills**
**(Based on 100 Per Cent Production in Shallow Basin)**

Basin produces on the average 79 per cent and Deep Basin about 65 per cent of the Conventional Still. Fig. 42 is essentially the same type of presentation except production from Shallow Basin Still III is assumed to be 100 per cent.

To understand the difference between operation of Shallow and Deep Basin it would be of value to study the hourly variation of temperature of water in these two stills. Fig. 43 shows such a variation. The only difference between these two stills is the quantity of water inside them. Early in the morning, water in Still I is at a higher temperature, as the sun rises temperatures of water in both stills rise. However, water in Still III rises at a faster rate and by 10 a.m. equals Still I. As the day progresses, water in Still III gets hotter and the increasing temperature continues until about 3 p.m. At this time temperature in Still III starts to drop but in Still I continues to rise for another three hours. This can be explained if we consider that at 3 p.m. water temperature in Still III is considerably high, high enough so that its losses are exceeding the low solar energy income. On the other hand, the temperature in Still I is relatively low and incoming energy exceeds the losses, therefore temperature rises until these two balance each other. After that, the temperature will drop. Drop of temperature between 1 and 2 p.m. indicates that Still I is less susceptible to sudden variation of solar energy. At sunset both temperatures drop but Still III at a faster rate. These two curves reasonably well explain the operation of these two stills. Considering the ambient temperature in the Fig. 43, the reason for night production of Still I and day production of Still III is explainable.

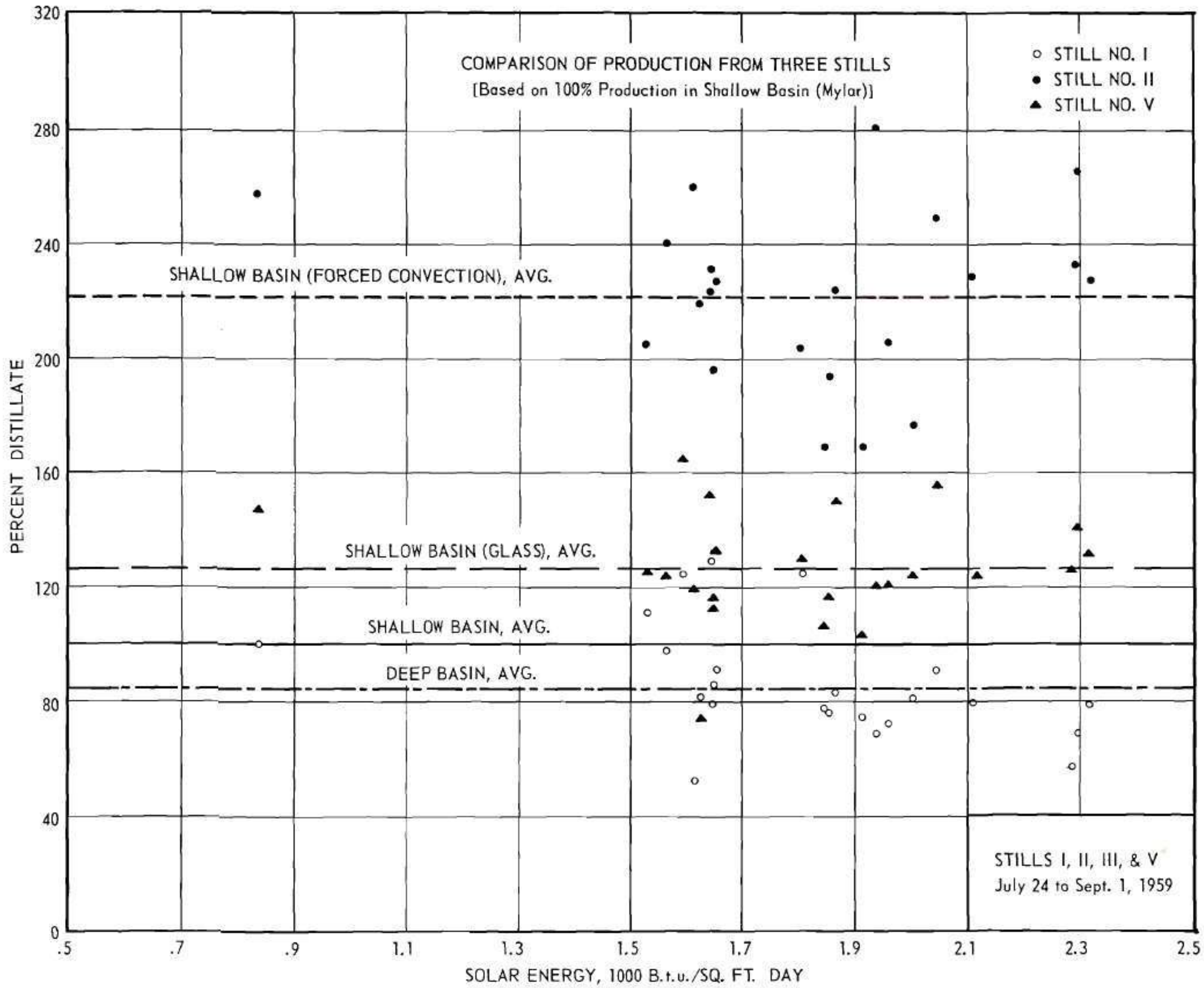



Figure 42.

**Comparison of Production from Three Stills**
**[Based on 100 Per Cent Production in Shallow Basin (Mylar)]**

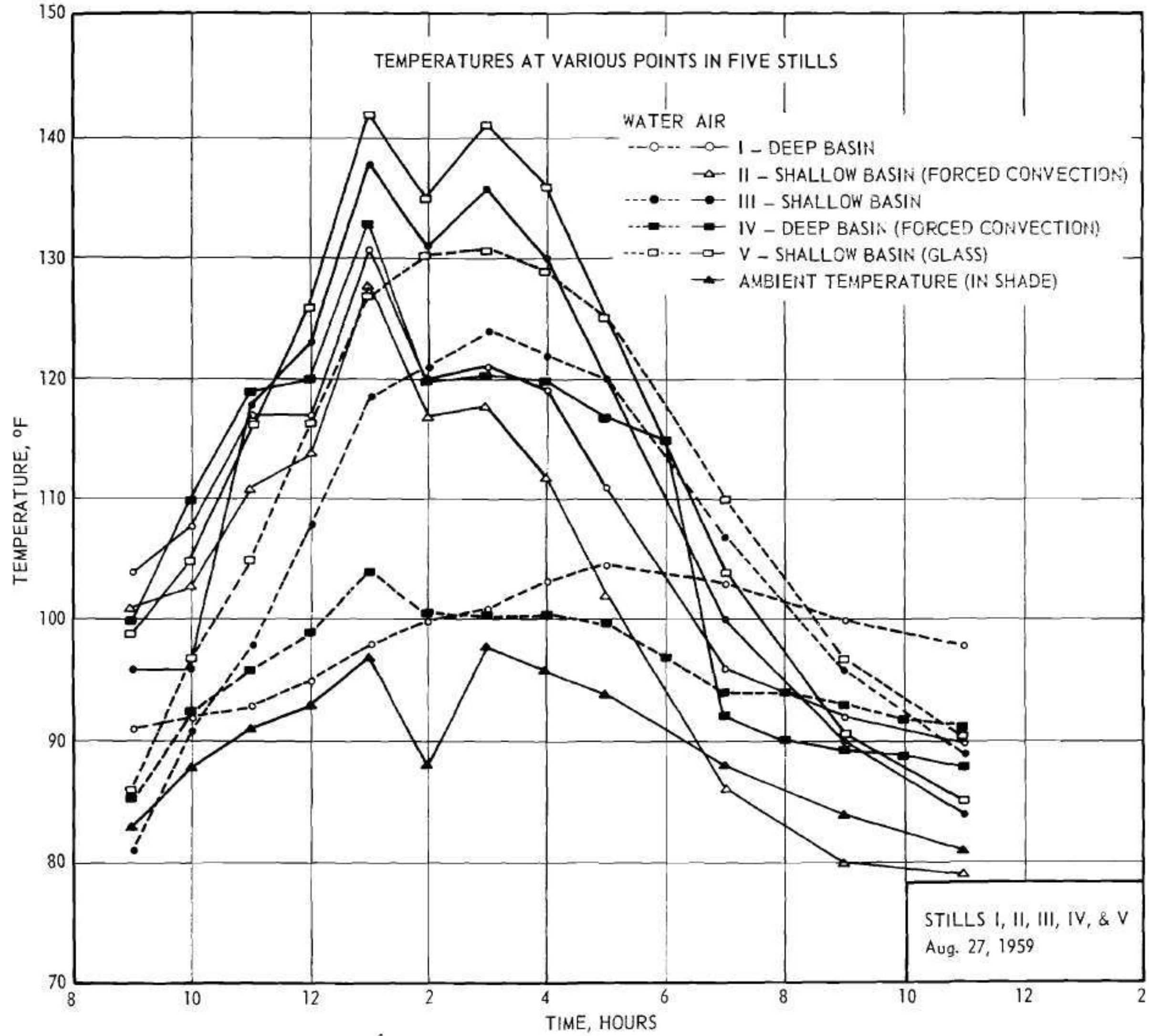



Figure 43.
**Temperatures at Various Points in Five Stills**

# CHAPTER VI

## ECONOMY OF PROCESSES

To explore the economic feasibility of saline water conversion by solar distillation one faces a rather complicated problem.

In practice two different situations may be encountered, 1) where the process of solar distillation must be evaluated against conventional sources of supply and 2) where it must be studied against other methods of converting sea water to fresh. The second situation is encountered in places where salt and brackish water are the only sources of supply.

Both of these situations must be investigated specifically for the location in which the study is being conducted. Any generalization must be accepted cautiously and be treated according to its limitations. A process which may prove to be economically feasible in one location may be completely unattractive in another location. As an example, electrodialysis is a leading method of conversion that is used where the salinity of water is low and electricity is inexpensive. However, the same process is unattractive for converting sea water that has a high salt concentration. The process will be even less attractive when electricity is more costly.

It has been shown that diversity of conditions associated with saline or brackish water purification can not be met by a single process. The great variations in mineral content of waters and in the uses which may be made of the demineralized water in different locations suggest that various processes will be needed to attain maximum economy for a given situation. Utilization of solar distillation is attractive because the sun's energy is free and permanent. Many areas of the world receive large amounts of sunshine. The most important limitation is the high cost of construction, equipment, and maintenance. Another serious difficulty is the relatively large area needed. This is a very important consideration in the congested areas of the world.

It is obvious that solar distillation is worthy of careful examination where a plentiful amount of solar energy is available and land is inexpensive. Another factor in favor of the use of solar stills is their simplicity. They do not require complicated installations and highly specialized labor, and the required construction materials are readily available anywhere in the world.

The total economy of the process includes; the energy cost, capital investment, and operational expenses. All of these must be included to estimate the total costs realistically. Reports made by numerous investigators in connection with the cost of construction and production are so varied that a comparison is impossible and published cost data are not consistent. In many of these reports such items as taxes, land, interest, labor, and building costs are often not considered at all. In the event they were estimated, their assumptions vary considerably.

The estimated cost, projected from a laboratory size model or calculations, covers a range from $1.25 to $20.00 per 1000 gallons of fresh water produced (59, 60, 67, 81).

It is of value to study the procedure that produced this low value of $1.25. This cost does not include labor and maintenance. The estimator, a prominent expert in the field, states (81):

> Thus, if an entire solar distillation plant can be completed at the optimistic price of $1.00 per square foot in a favorable location where 0.10 gallon of distilled water can be produced per sq ft each day. . . Publicly owned plants, with more economical financing possibilities might reduce the fixed costs to approximately $1.25 per 1000 gallon.

This clearly shows the procedure which was used to estimate the water cost. The magnitude of assumption probably will be better appreciated if it is realized that the actual estimate for the same plant was $7.00 per sq ft* for construction.

Consequently the purpose of this study is not to compare the economy of still construction and operation with the cost reported in the literature, but it is intended to show what may be expected from each design under similar conditions of those prevailing for Atlanta, Georgia. However, since the study is executed according to Standard Procedures set up by the Office of Saline Water for estimating cost of saline water conversion, the results will be comparable to any estimation made by their procedure.(91).

The cost estimation is based on a 100,000 gallon per day plant for these three types of design: Shallow Basin (I), Shallow Basin (Glass V), Shallow Basin (forced convection II) Stills. Deep Basin (I) and Deep Basin (forced convection IV) are omitted because at present they are not up to full efficiency.

It was found in Chapter V that the average yield from Still II is 170 per cent and for Still III is 79 per cent of the yield of

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*This is estimated cost for concrete deep basin design.

Still V which is the conventional design. These values are used for calculation. The distillate from Still II is assumed to be 1.2* lb/sq ft/24 hours and for other stills is calculated according to the established percentage. Tables 7, 8, and 9 show the necessary values for calculation:

Table 7. Area Requirement

| | Still III | Still V | Still II |
|---|---|---|---|
| Per cent yield | 79 | 100 | 170 |
| Average production on the basis of solar Still II, lb/sq ft/day | 0.55 | 0.70 | 1.2 |
| Area required for 100,000 gallons per day production in sq ft | 1,517,260 | 1,192,140 | 695,410 |
| Excess transparent materials required to form the canopy, per cent | 40 | 40 | 20 |

Table 8. Unit Cost

| | |
|---|---|
| Mylar, type W | $2.50 per 28 sq ft |
| Double strength glass 1/4" thickness | .50 per sq ft |
| Frame, No. II | .20 per sq ft |
| Frame, No. III and V | .30 per sq ft |

*1.2 lb/sq ft/24 hours is the average of the six highest points produced by Still II. It is felt that this is still conservative because Atlanta lacks solar energy expected in a proper location for solar still construction.

Table 9. Years of Amortization

| | |
|---|---|
| 1. Mylar, type W | 4 years |
| 2. Glass | 20 years |
| 3. Other parts | 20 years |

The following approximate costs are estimated according to the Standard Procedure established by the Office of Saline Water.

| Capital Costs | Still III | Still V | Still II |
|---|---|---|---|
| Essential Plant Costs: | | | |
| 1. Special Equipment (installed) | | | |
| a. Solar Still Frame, including insulation | $ 455,178 | $ 357,642 | $ 139,082 |
| b. Weatherable Plastic, Type W, or Glass | 189,657 | 834,498 | 74,508 |
| 2. Standard Engineering Equipment (installed) | | | |
| a. Heat Exchanger | -- | -- | 50,000 |
| b. Pump and Blower | 2,000 | 2,000 | 7,000 |
| Total PIE (principal items of equipment)(installed) | $ 646,835 | $1,194,140 | $ 270,590 |
| 3. Erection assembly of plant, 30 per cent of PIE | 194,050 | 358,242 | 81,177 |
| 4. Instruments - 4 per cent of PIE | 25,873 | 47,765 | 10,823 |
| Total Essential Plant Costs (1 through 4) | $ 866,758 | $1,600,147 | $ 362,590 |
| Other Plant Costs: | | | |
| 5. Raw Water Supply, $5 per 1,000 gallons feed water per stram day | 1,000 | 1,000 | 10,000 |
| 6. Product Water Storage (10 days) at $10 per 1,000 gallons product water per stream day | 1,000 | 1,000 | 1,000 |

| Capital Costs (cont.) | Still III | Still V | Still II |
|---|---|---|---|
| 7. Service Facilities and Buildings, 10 per cent of PIE for plants of 10 million gal/day capacity. Omit for plants of 100,000 gal/day | N/A | N/A | N/A |
| 8. Contingencies, 10 per cent of total of above 7 items | 86,875 | 160,214 | 37,359 |
| 9. Engineering, 10 per cent of above 8 items | 95,563 | 176,236 | 41,094 |
| 10. Interest on Investment during Construction, 4 per cent of plant investment (sum of above 9 items) | 42,047 | 77,543 | 18,081 |
| 11. Site $6 per 1,000 gallons of product water per stream day | 600 | 600 | 600 |
| Total Plant Investment (sum of above 11 items) | 1,093,843 | 2,036,746 | 470,724 |
| Working Capital: | | | |
| 60 days production at the total operation cost | 20,000 | 20,000 | 12,000 |
| Total Capital Costs (plant investment plus working capital) | 1,113,843 | 2,036,740 | 482,724 |
| Cost per gallons per day of production | $11.14 | $20.37 | $4.83 |
| OPERATING COSTS | | | |
| Essential Operating Costs (basis, one stream day) | | | |
| 1. Fuel at 25 cents per 1,000,000 BTU | N/A | N/A | N/A |
| 2. Electric Power, below 100,000 KW, 7 mills per KWH | 3.00 | 3.00 | 30.00 |
| 3. Steam, $0.55/1,000 lb | N/A | N/A | N/A |
| 4. Other raw materials or chemicals used in the process | N/A | N/A | N/A |

| OPERATING COSTS | Still III | Still V | Still II |
|---|---|---|---|
| 5. Supplies and maintenance materials, 0.0015 per cent of total plant investment (items 1 through 11 under-capital costs)(0.5 per cent per annum, 330 operating days) | 16.41 | 30.25 | 7.06 |
| 6. Operating labor, 10 per cent of above 5 items plus amortization (see Item 10, a and b) for plants of 100,000 gal/stream day | 37.74 | 49.70 | 18.68 |
| 7. Maintenance labor, 0.0015 per cent of total plant investment (0.5 per cent per annum) | 16.41 | 30.25 | 7.06 |
| 8. Payroll extras, 15 per cent of items 6 and 7 | 8.12 | 11.99 | 3.86 |
| Total Essential Operating Costs (sum of above 8 items) | 81.68 | 125.19 | 66.66 |
| Other Operating Costs | | | |
| 9. General overhead and administrative overhead, 30 per cent of items 6, 7, and 8 | 18.68 | 27.58 | 8.88 |
| 10. Amortization | | | |
| a. Plastic (4-year life) | 155.51 | -- | 61.09 |
| b. For equipment (20-year life), and glass | 202.54 | 451.75 | 88.75 |
| 11. Taxes and Insurance, 0.0061 of TPI | 65.63 | 121.00 | 28.24 |
| 12. Interest on working capital (0.012%) of working capital (4% per annum). Calculate as .00725 times the sum of the above 11 items. | 2.40 | 2.40 | 1.44 |
| Total Operating Costs for one stream day (sum of above 12 items) | 526.44 | 727.92 | 255.06 |
| Cost per 1,000 gallons of product water | $5.26 | $7.28 | $2.55 |

The economical advantages of design II and III over the conventional Still V is clearly shown. Both capital cost and per 1,000 gallons operations cost are definitely lower for these two stills.

Cost, in terms of depreciation, in the conventional design is estimated optimistically since the purpose of the estimate is to show a comparison rather than an absolute value. However, the calculations were made as realistic as possible. The plastic (Mylar, type W) canopy shows an advantage over glass. This is due to the difference of initial cost which is considerably less for Mylar. Another hidden advantage of Mylar over glass is its light weight and ease of handling. Mylar, being much lighter, tends to be more practical in remote areas.

The distinct advantage of the shallow basin over the shallow basin (forced convection) design is that the former does not require a blower and heat exchanger. This may be of greater significance in underdeveloped countries, where simplicity is of prime importance.

It is seen that the cost of conversion is high, despite free energy. Few users are willing to pay for the water at these costs. The highest cost that is paid for water in the average American city in 1952 was about \$.38 per thousand gallons (92). Today's cost corrected by Eng. News Record Construction cost index (93) is about \$.53 which is still considerably lower than the estimated cost of water by any modification of solar distillation equipment. However, all communities are not as fortunate as the average American city. There are many of them that would be willing to pay a much higher rate for a good reliable supply of water. The citizens of the Island of St. Thomas in the Virgin Islands, for example, would like very much to use converted water if it could be produced for less than \$5 per 1,000 gallons (2), the price of potable water brought in by barge. Coalinga, California, for years paid \$7 per 1,000 gallons of water brought in by train. The cost is cut to an estimated \$1.45 per 1,000 gallons for conversion of brackish water by electrodialysis. Coalinga is the first city in the United States of America that is using converted brackish water (2).

# CHAPTER VII

## CONCLUSIONS AND RECOMMENDATIONS

On the basis of the observations made and data collected during the investigations underlying this study, the following conclusions may be drawn:

1. Deep-basin produced overnight rather than during the daylight hours. The night production on the average was 160 per cent of the daylight hours production.

2. Insulation increased the efficiency of the deep-basin if production was more than 0.265 lb/sq ft/day and decreased if it was below that value. (This was caused because the stills were elevated above the floor level.)

3. Dropwise condensation, an inherent property of type W, Mylar, although more effective as a condensation process, reduced the over-all efficiency to 79 per cent of sheet condensation, a property of clean glass. The effect is due to the increase of the index of reflection.

4. Forced convection effectively removed the condensate from beneath the canopy. Therefore, there were no losses due to absorption and reflection by condensate.

5. Production was a function of solar energy. It appears to be a linear relationship and directly proportional to the solar energy. However, the experiment was performed under 2500 BTU/sq ft/day insolation.

Other investigators reported that above this value the production from the conventional still will fall.

6. The straight line of best fit to the plot of distillate versus solar energy, shows a greater slope for Still II than any of the others. This indicates the relative production will even be better with higher solar energy.

7. The efficiency of all the stills was found to be quite constant over the range of solar intensity which was experienced during the experimental period (800 to 2500 BTU/sq ft/day). However, some scatter in the data was observed.

8. Mechanical separation of the collector-evaporator unit from condenser plus forced convection increased the amount of average distillate from 79 per cent (Still III) to 170 per cent (Still II) as compared to the conventional still (Still V).

9. Operation of the Stills II and IV, with forced convection was found to depend on the amount of air used to carry the vapor through the stills.

10. Employing the principle of heat balance, an expression was developed which enables an intelligent estimation of water production from a deep basin (forced convection) still. A graphical solution is presented to facilitate the calculations.

11. Droplet evaporation, although imperfectly achieved, increased the production approximately from 72 per cent of the conventional for flat sheet evaporation, to 119 per cent in a typical day.

12. The average and maximum production values for different stills in lb/sq ft/day, were as follows:

| | Average | Maximum |
|---|---|---|
| Still I | .312 | .526 |
| Still II | .848 | 1.224 |
| Still III | .349 | .592 |
| Still V | .499 | .698 |

13. A cost estimate is made according to the procedure set forth by the Office of Saline Water, U. S. Department of the Interior. The following results were found:

| | Still II | Still III | Still V |
|---|---|---|---|
| a. Capital cost per one gallon daily production | $4.83 | $11.14 | $20.37 |
| b. Operation cost per 1000 gallons product | 2.55 | 5.26 | 7.28 |

Stills I and IV were omitted from this study because they were not up to full efficiency.

14. Solar stills are simple and easy to operate, best suited to remote regions of the world, but capital cost is high, therefore yield is relatively expensive despite free energy.

As an outcome of these studies and analysis of the data presented herein, it is recommended that the following topics of the investigations be studied:

1. In the course of experimentation it was definitely found that the functioning of the heat exchanger is of prime importance in operation of stills with external condenser. Therefore, it is suggested that a direct contact heat exchanger be investigated. In such design the hot, saturated air from the collector-evaporator unit will come in direct contact, in the form of bubbles, with cooled fresh water in the storage tank. The fresh water will be cooled by raw incoming sea water.

2. To increase the rate of evaporation by droplet evaporation, different sprays and nozzles must be studied. Tray type dispersing mechanism which was tested in the course of this study must be further developed.

3. Study of larger stills is recommended so as to eliminate the wall effect and also increase the efficiency of heat exchanger. A humidity-sensitive element should be installed in the effluent line of the collector-evaporator unit to control the amount of air passing through the stills.

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## VITA

Mr. Iraj Zandi was born at Teheran, Iran, on June 30, 1931, the son of a civil engineer. He grew up in Teheran and attended the University of Teheran from 1948 to 1952 and received his B.S. degree in Electro-Mechanical Engineering in June 1952.

Upon graduation he joined the Ministry of Health, Government of Iran, initially as Asst. Sanitary Engineer. In 1954 he was promoted to Sanitary Engineer and in 1955 was made Acting Chief, Water Supply Branch, Division of Sanitary Engineering, Department of Health. Later in the same year he was transferred to the Province of Isfahan and became Chief of the Sanitary Engineering Division for the provincial health department.

In 1956 he was sent to the United States to further his education under the auspices of the International Cooperation Administration, U.S. Department of State, and began to attend the University of Oklahoma, Norman, Oklahoma, in the fall of that year. Mr. Zandi received a M.S. degree in Civil Engineering from the University of Oklahoma in June 1957. The title of his M.S. thesis was "Sewage Stabilization Ponds as a Sewage Treatment Facility."

Upon receipt of his master's degree, Mr. Zandi attended a short course on communicable disease control sponsored by the U.S. Public Health Service. In the summer of 1957 Mr. Zandi came to the Georgia Institute of Technology to pursue a program of studies leading to the doctorate degree.

In July 1959, Mr. Zandi was elected as a member of the Georgia Tech Chapter, the Society of Sigma Xi.

Mr. Zandi was married in June 1958 to the former Annette Marie Grantham and they have a five months old son.